



Solar Sailing

What are we waiting for ?

Solar Sail Technologies and Applications Conference
NASA/GSFC 28-29 September 2004

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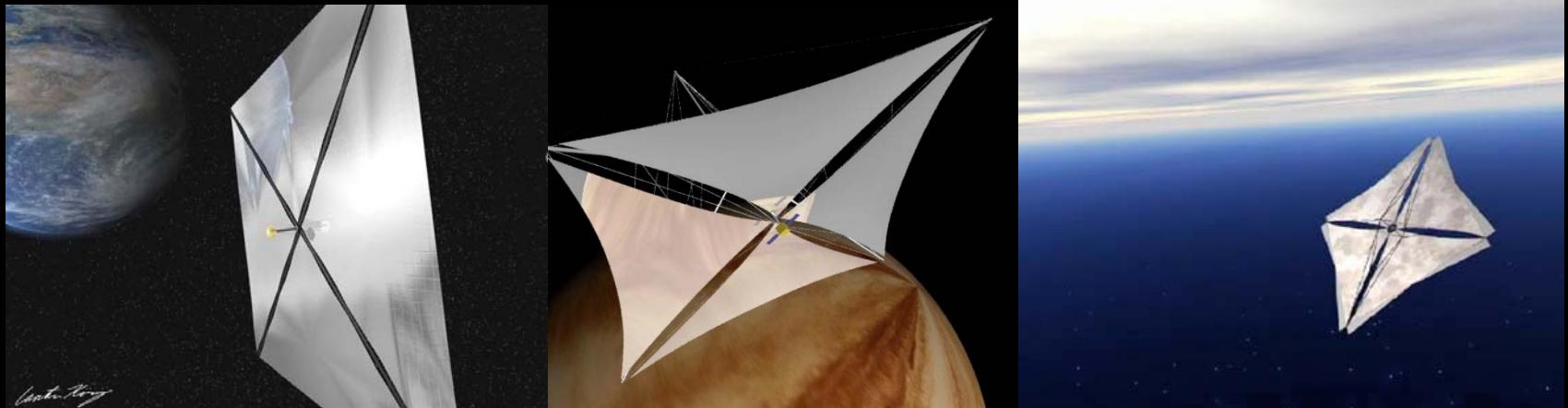
Presentation Overview

- **Introduction to solar sailing**
- **Component technologies**
- **Solar sail orbits**
- **Near-term missions**
- **Mid-term missions**
- **Far-term missions**
- **Future Prospects**

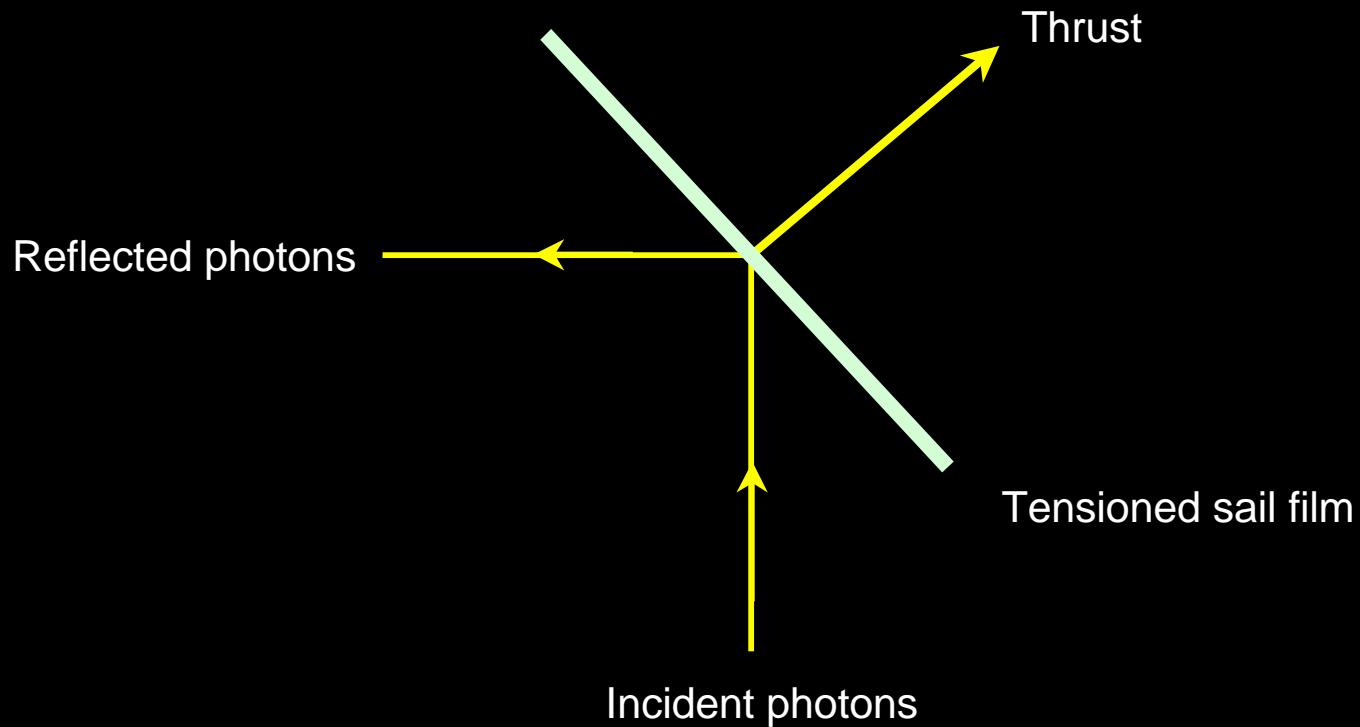
➤ Introduction to Solar Sailing

Solar Sailing

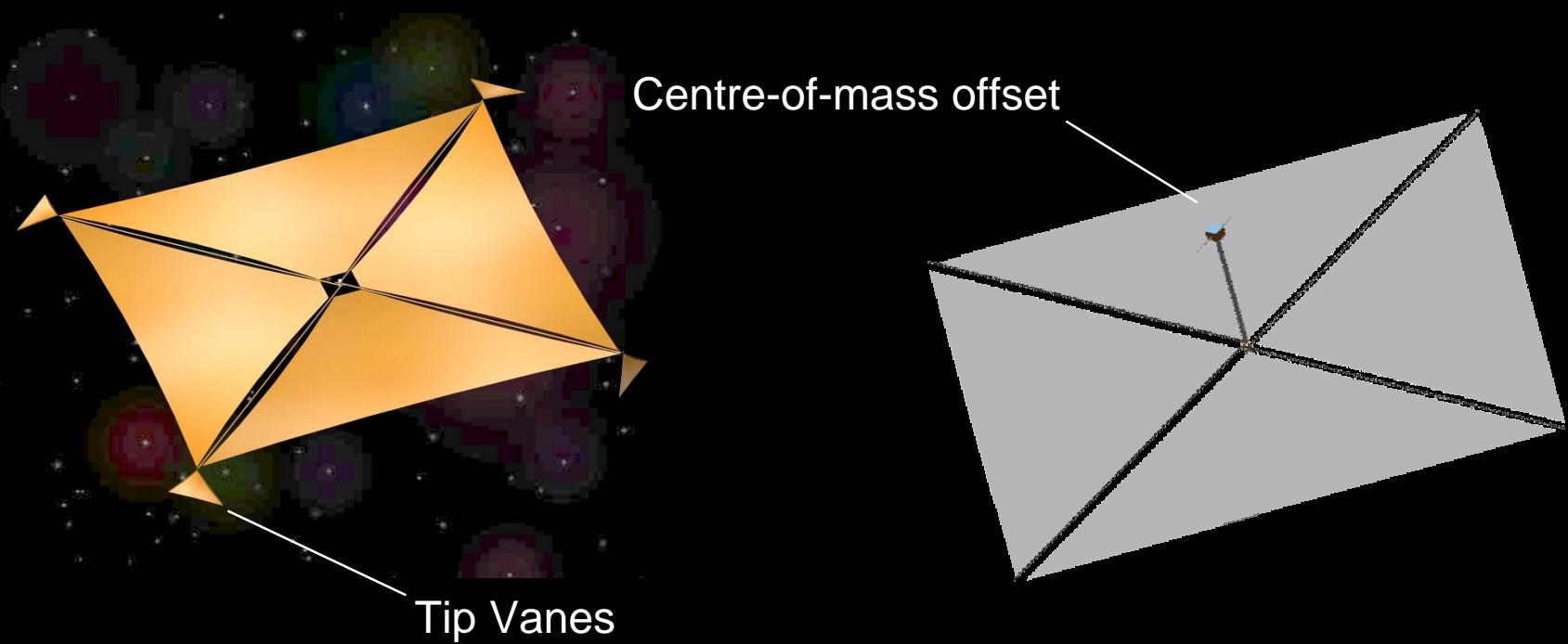
- Utilise light pressure for propulsion – small, but continuous acceleration
- No propellant required – can **enable** new high energy/long duration mission concepts
- **Enhance** existing mission concepts – reduce launch mass or increase delivered mass
- Provide **unique vantages points** for space science, Earth observation, telecomms.
- Numerous technology issues – thin films, deployable structures, control



Light Pressure



Attitude Control



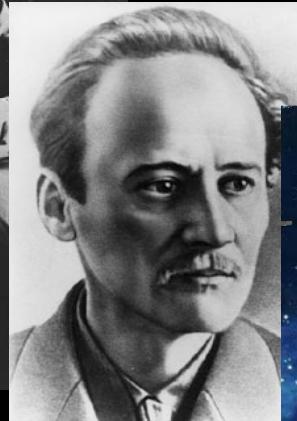
Historical Background



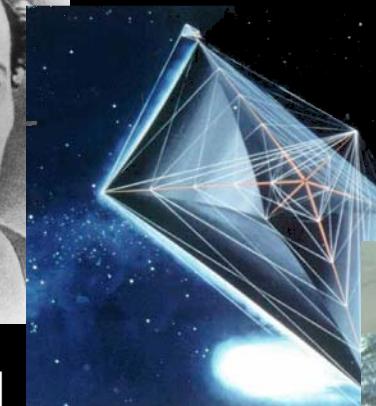
Maxwell: 1873



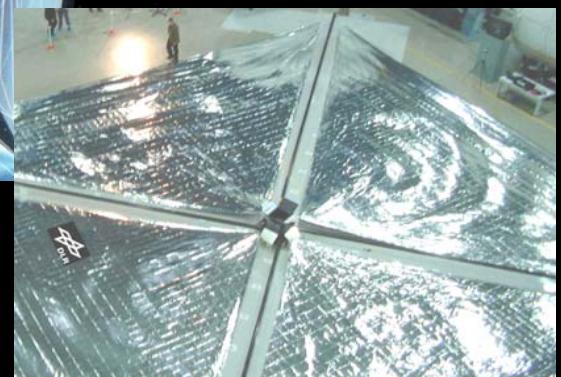
Tsiolkovski: 1921



Tsander: 1924

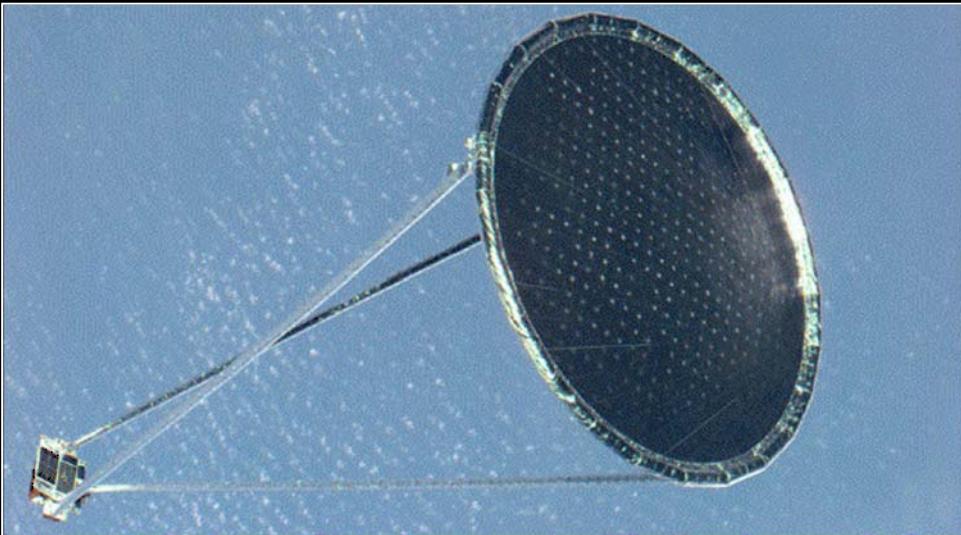


1977 JPL 800 x 800 m comet Halley sail

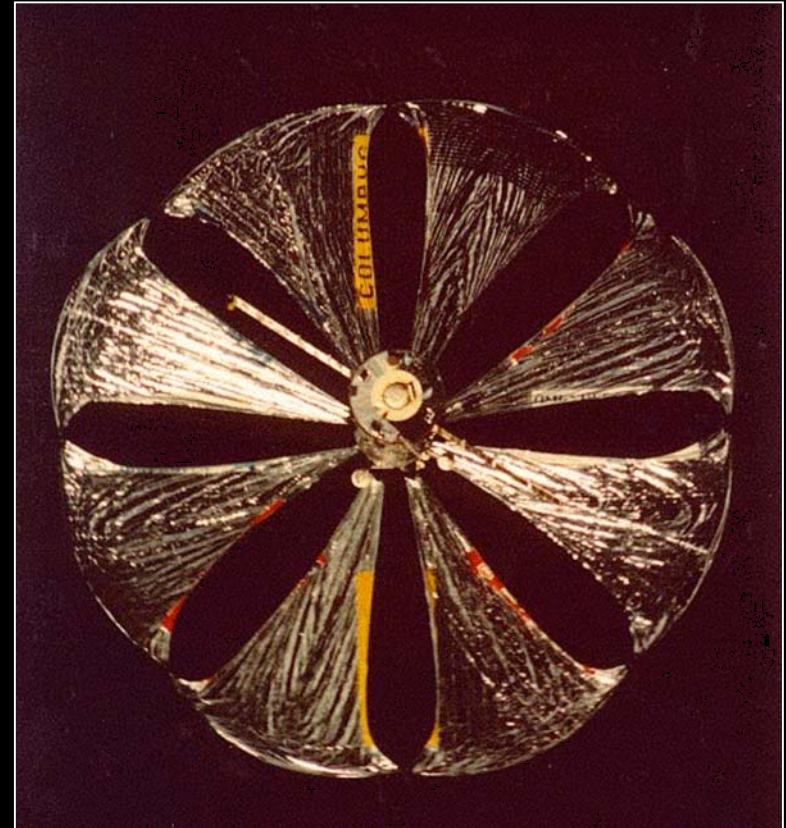


1996 - growing NASA and ESA interest

Past Activities

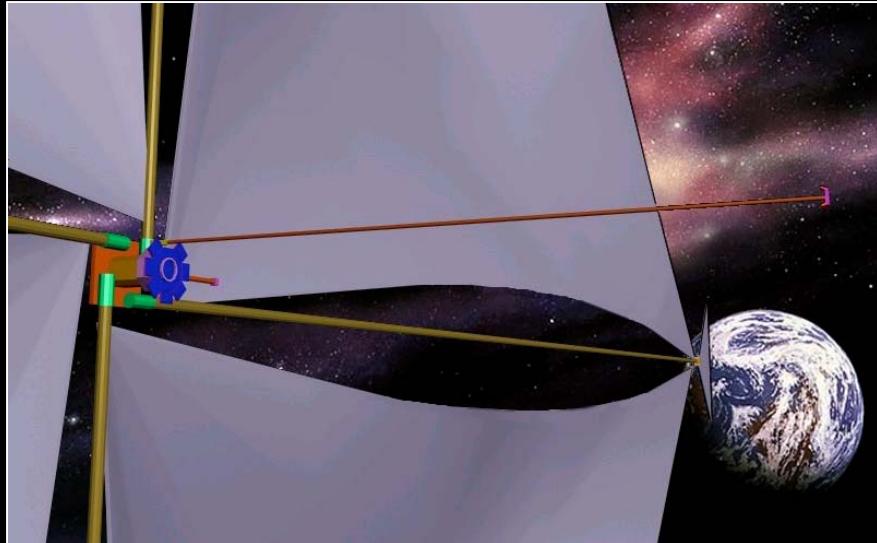


IAE experiment 1996

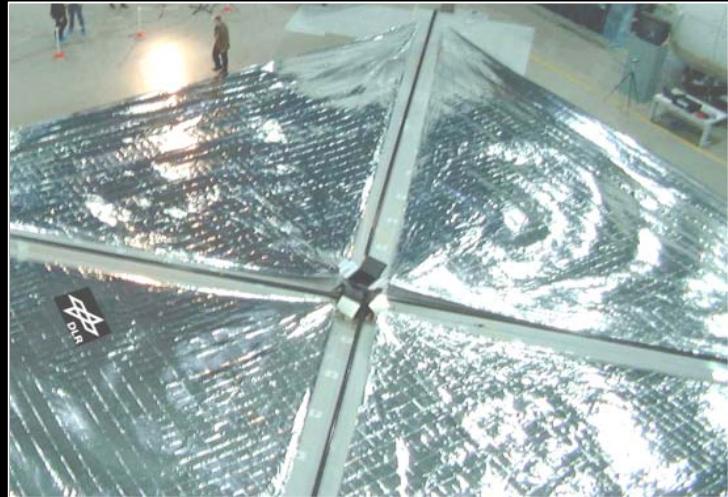


Znamya reflector 1993

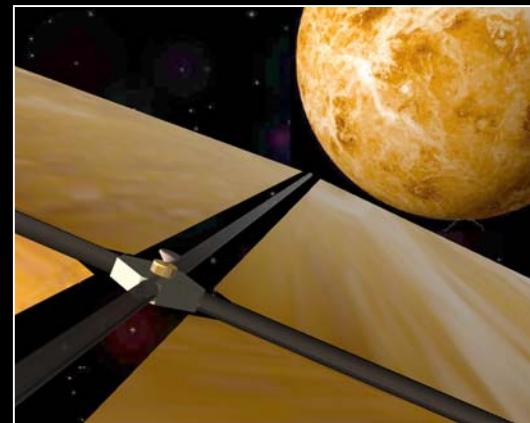
Recent Activities



NASA studies/deployment tests
CP-1 film production, booms



ESA/DLR 20 x 20 m ground test



New science mission concepts

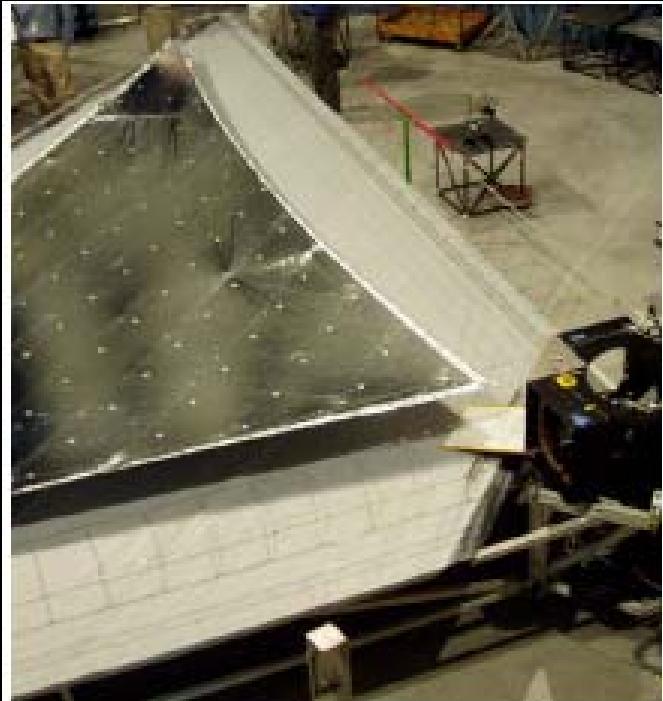
ESA Ground Test 1999



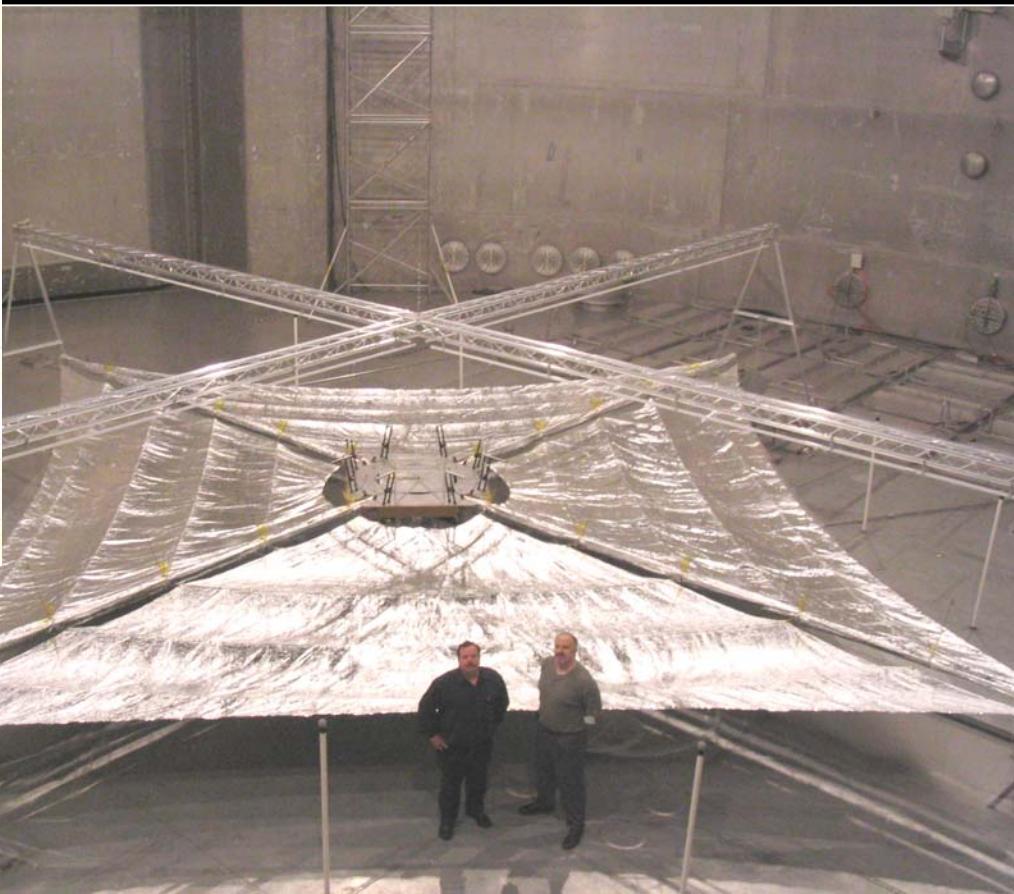
20 x 20 m ESA test



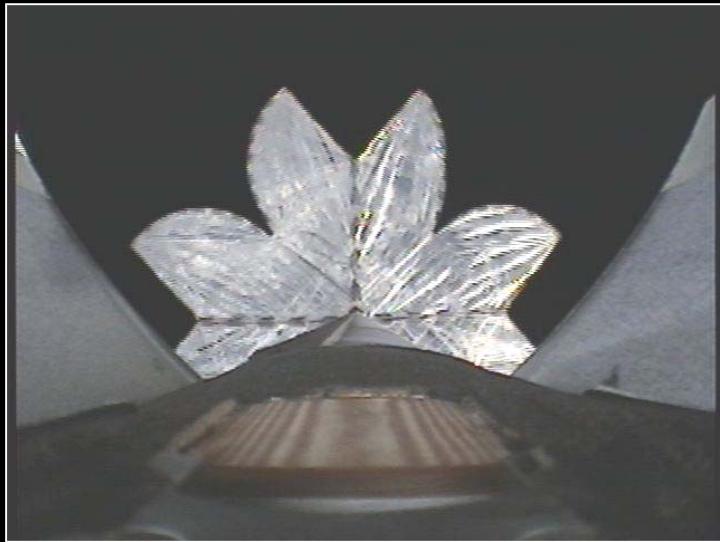
NASA Ground Tests 2004



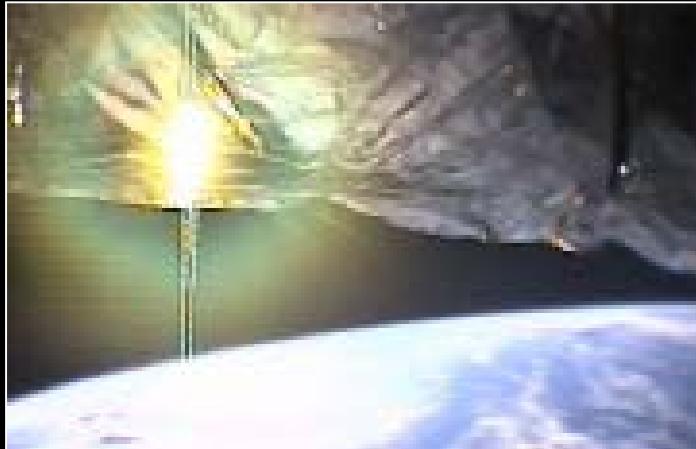
10 m AEC test



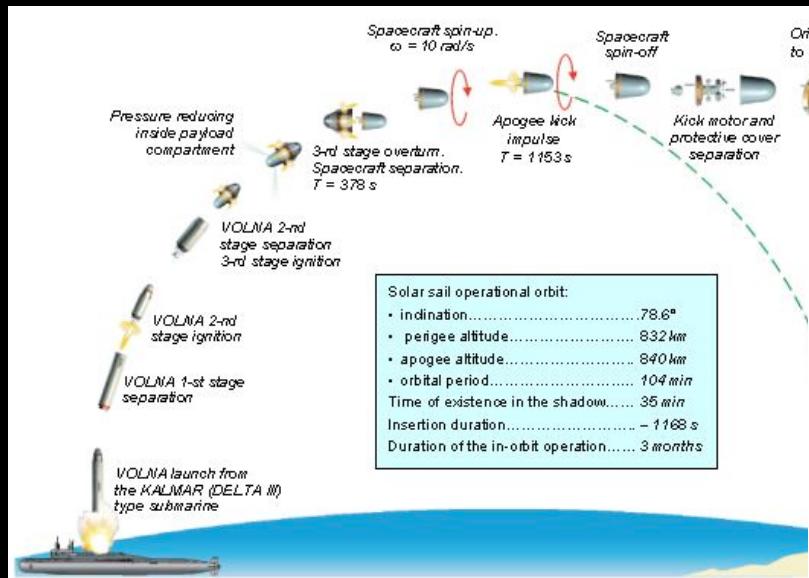
JAXA Sub-Orbital Test 2004



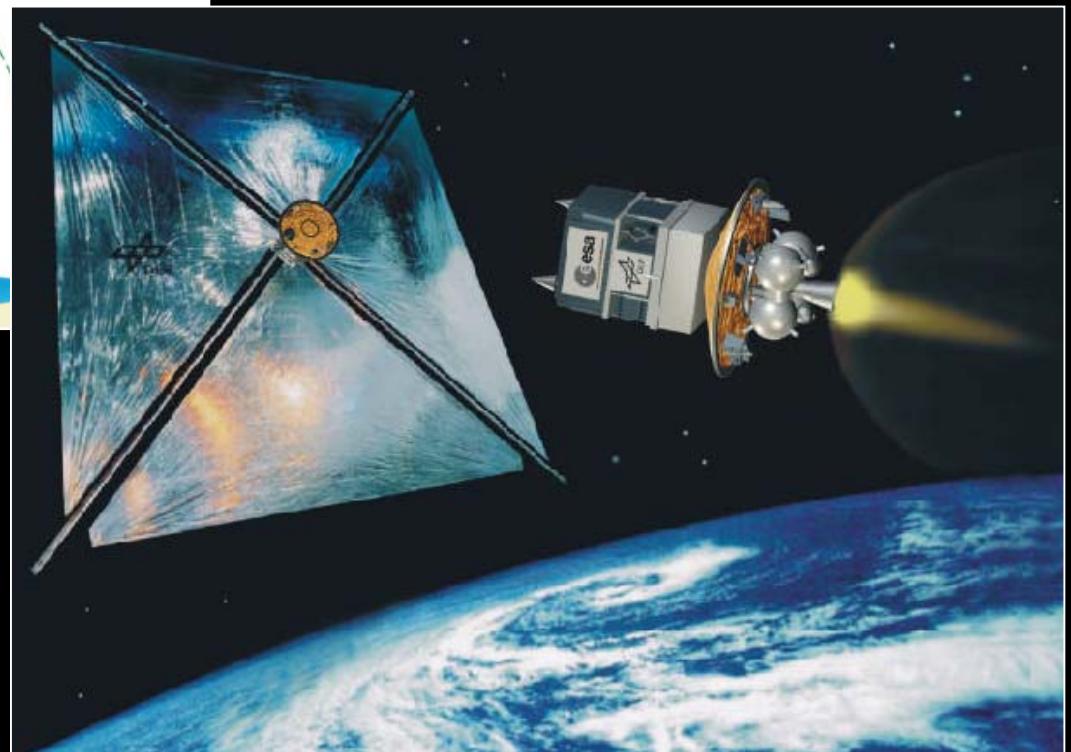
JAXA sail tests (x2)



Future Activities



Cosmos-1 (2004)



ESA deployment demo



Key Parameters

➤ Characteristic acceleration (mm s⁻²)

Sail acceleration at 1AU

Current capability 0.1 - 0.25

Requirement 0.10 (Near) - 0.5 (Mid) - 3+ (Far)

➤ Assembly loading (g m⁻²)

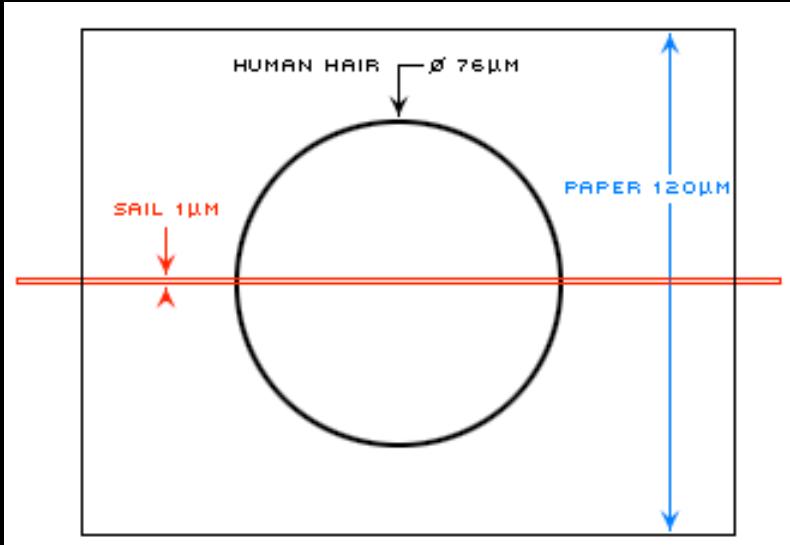
Ratio of sail film + structure mass to sail area

Current capability 30 - 15

Requirement 30 (Near) - 10 (Mid) - 1.5 (Far)

➤ **Component Technologies**

Sail Film Technologies



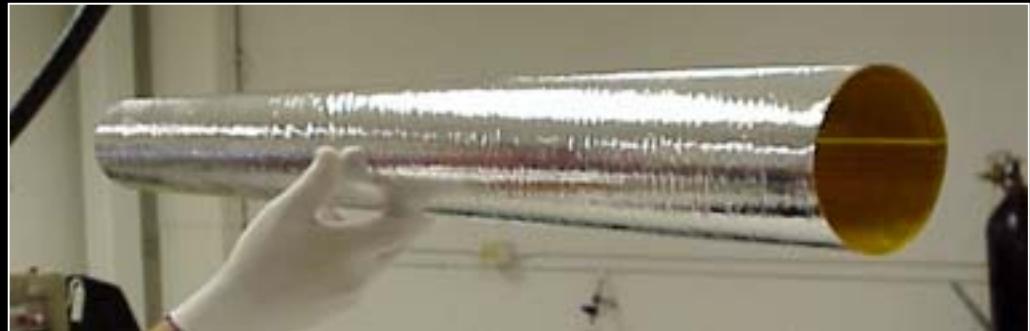
0.9 µm Mylar (L'Garde)

CP-1 (SRS)



Sail Boom Technologies

Coilable (AEC-Able)

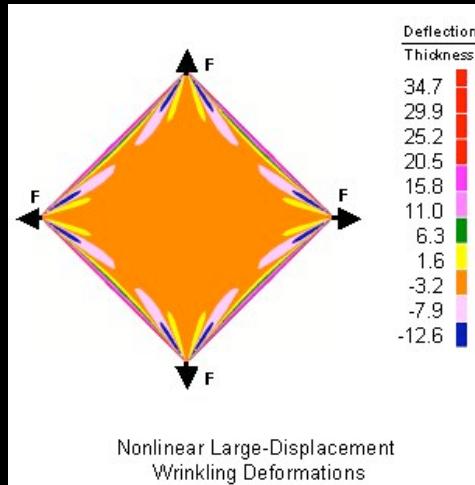


Inflatable - space rigidised (L'Garde)

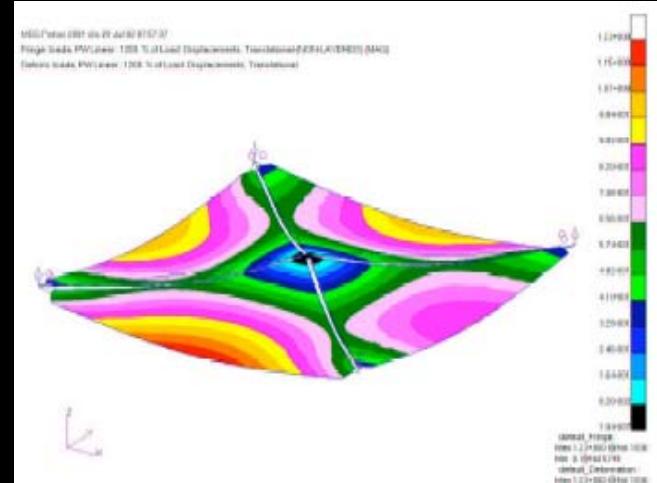


Composite (DLR)

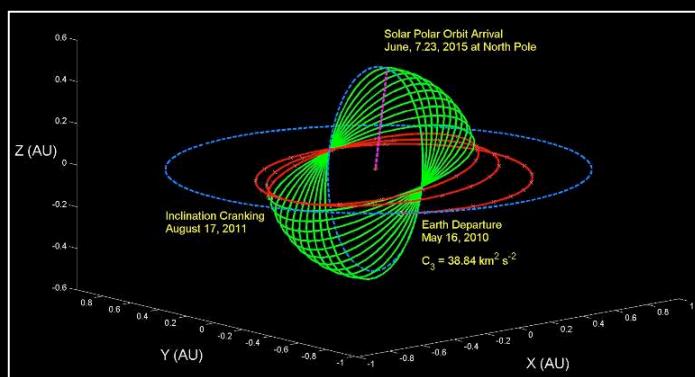
Analytical Tools



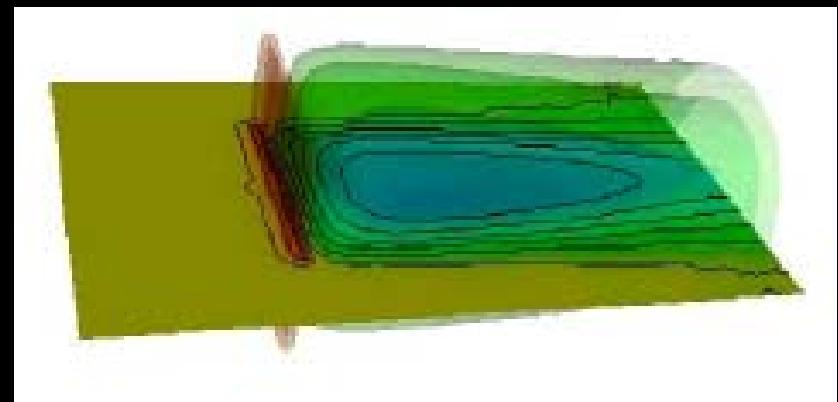
Wrinkling (NASA/Langley)



FE models (Duke Univ)



Trajectory optimisation

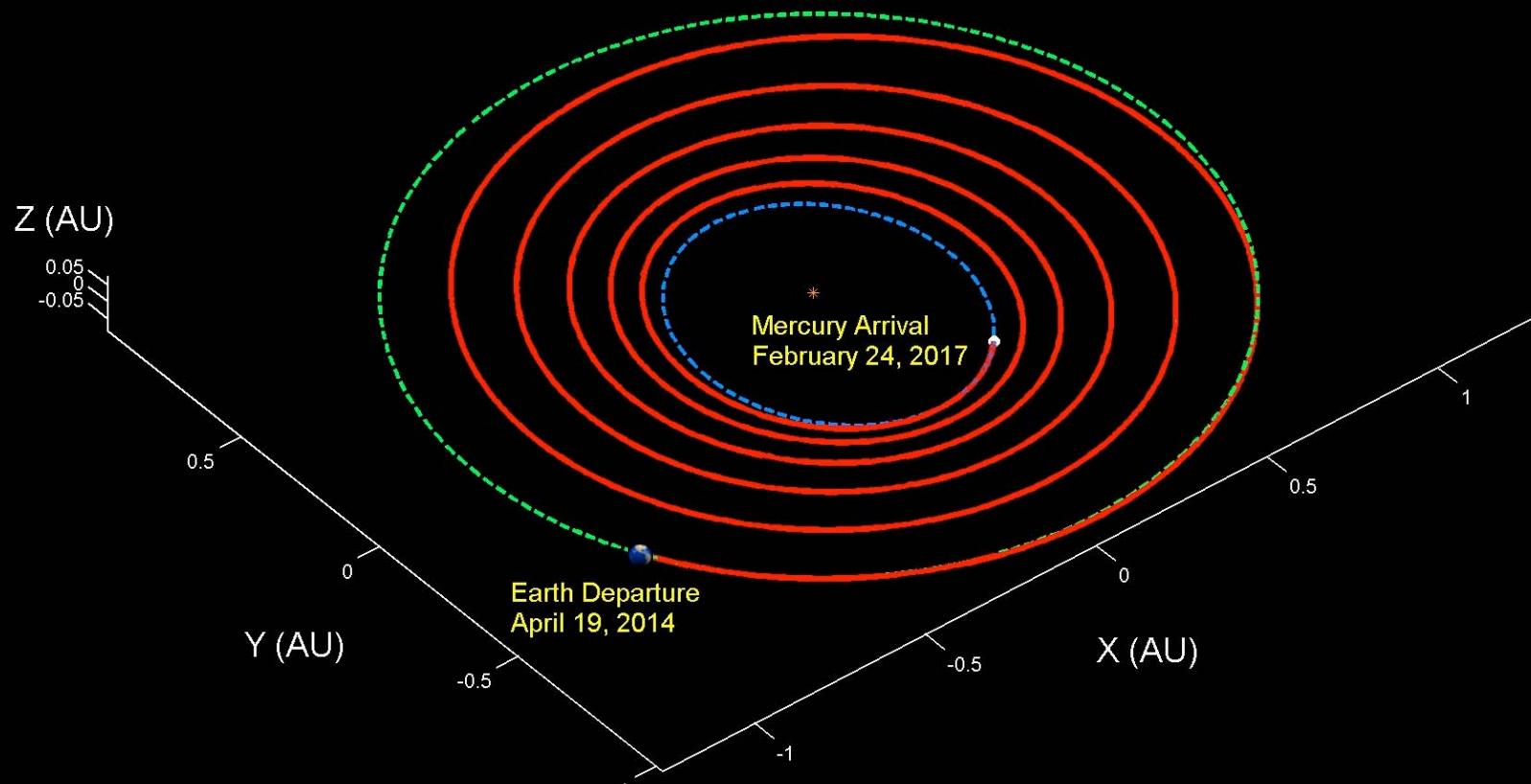


Plasma effects (NASA/JPL)

➤ Solar Sail Orbital Mechanics



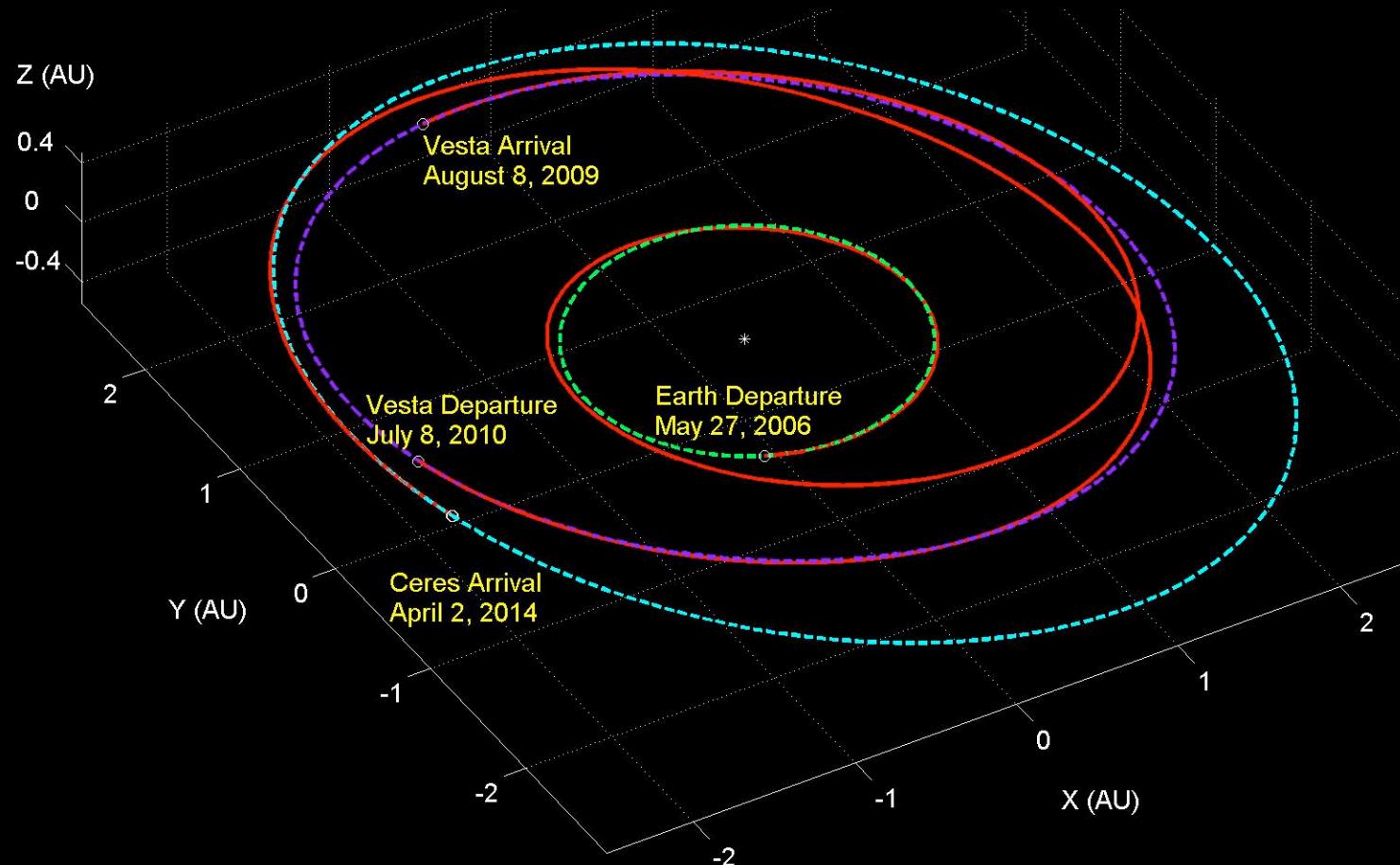
Planetary Rendezvous



0.25 mms⁻² sail - 2.83 yr trip



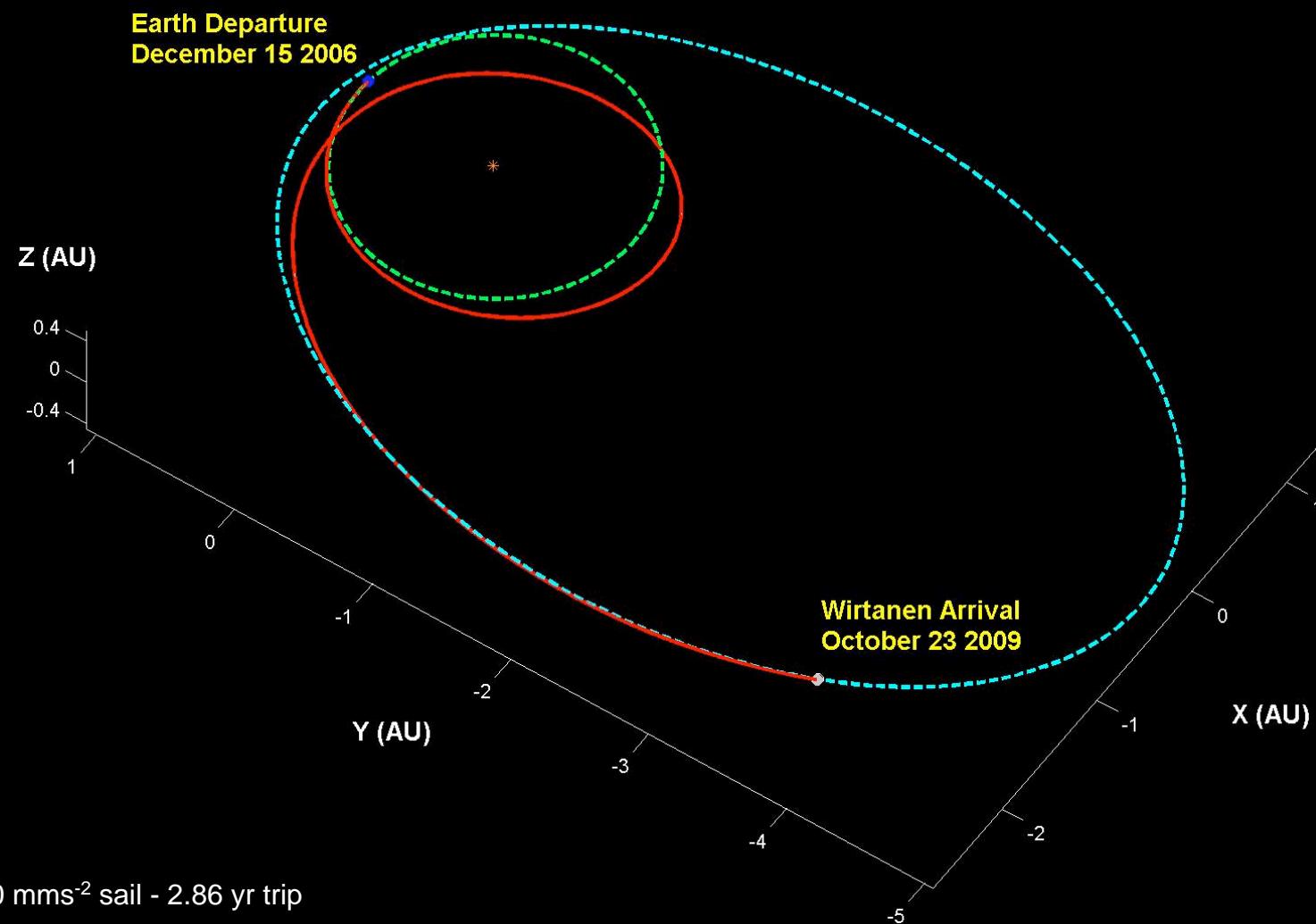
Small Body Tours



1.0 mms⁻² sail - 3.20 yr trip to Vesta

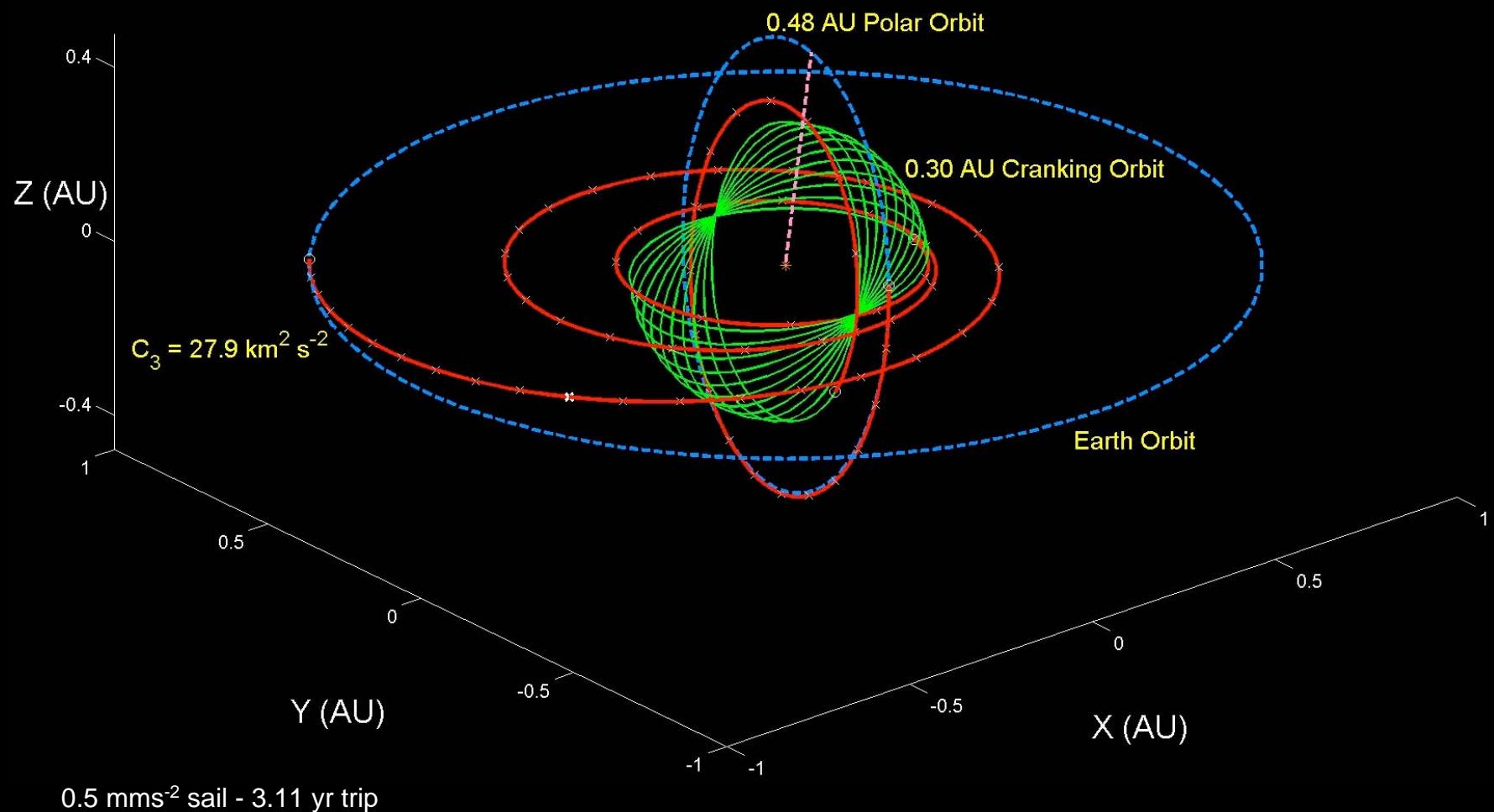


Comet Chasing





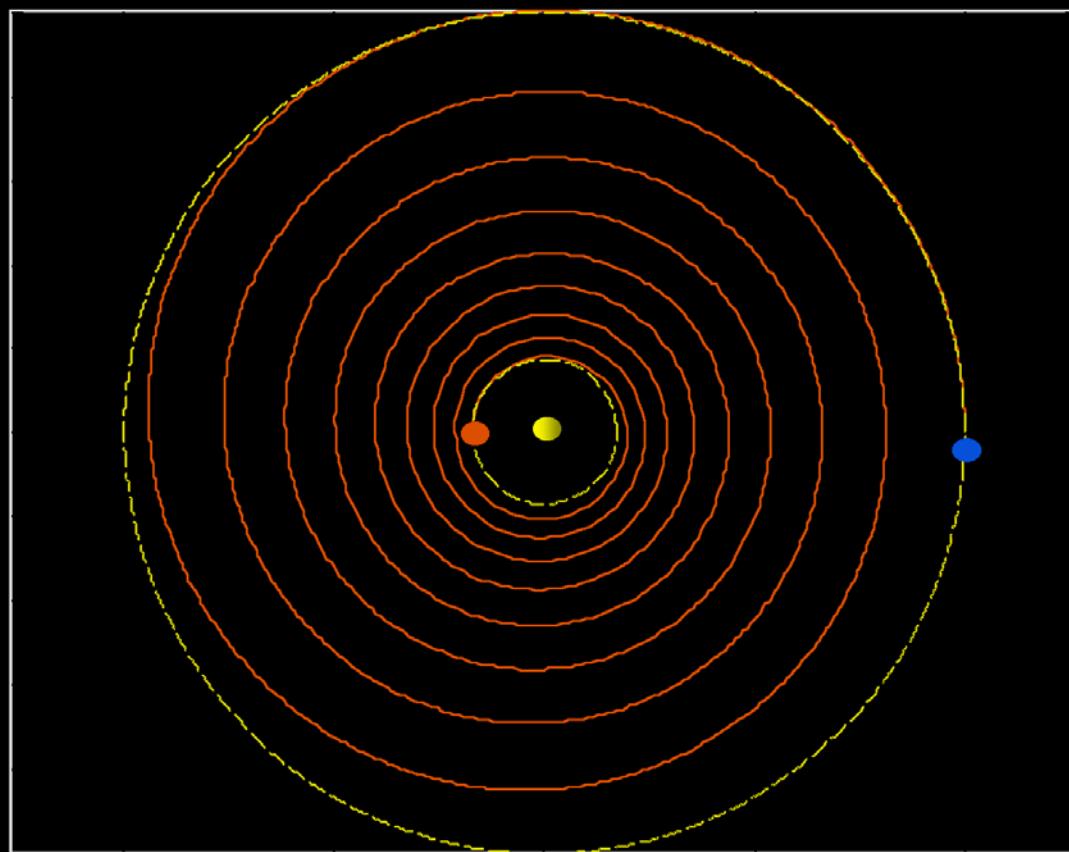
High Inclination Trajectories





Solar Synchronous Orbiter

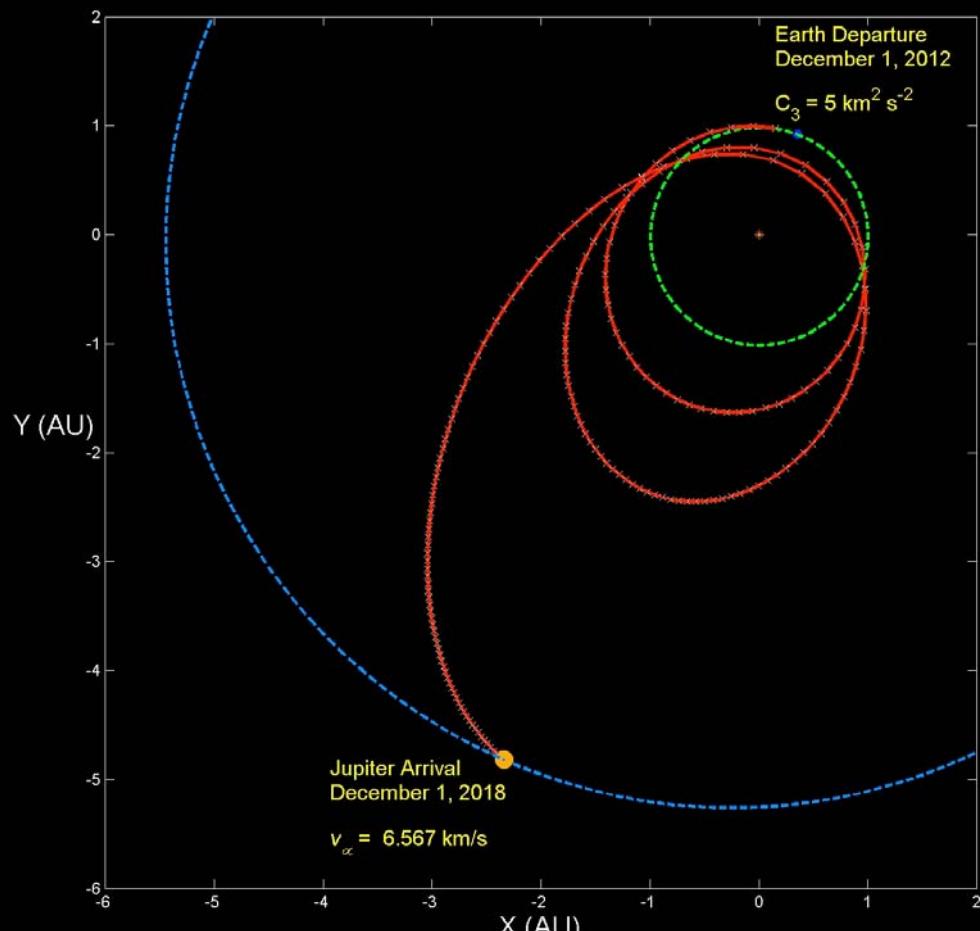
-1-0.500.51-0.8-0.6-0.4-0.200.20.40.60.81x (AU) Launch C³=0



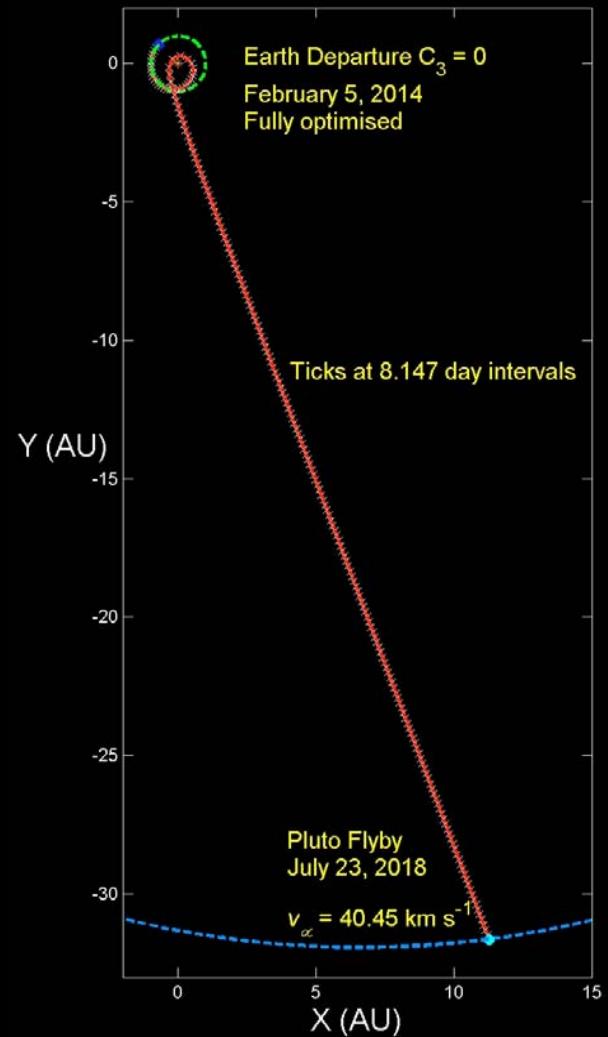
0.5 mms⁻² sail - 1.64 yr trip



Outer Solar System



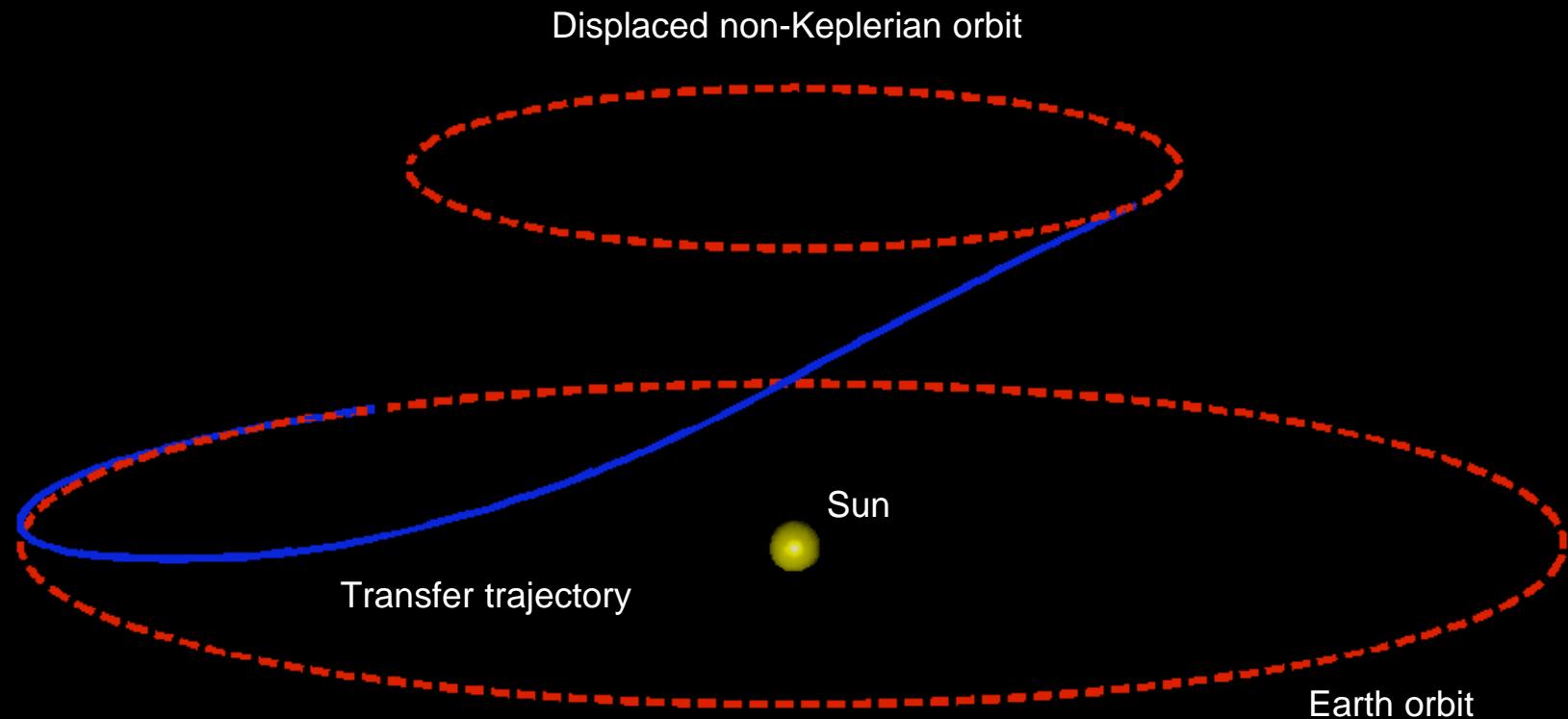
0.36 mms⁻² sail - 6.00 yr trip



3.0 mms⁻² sail - 4.46 yr trip



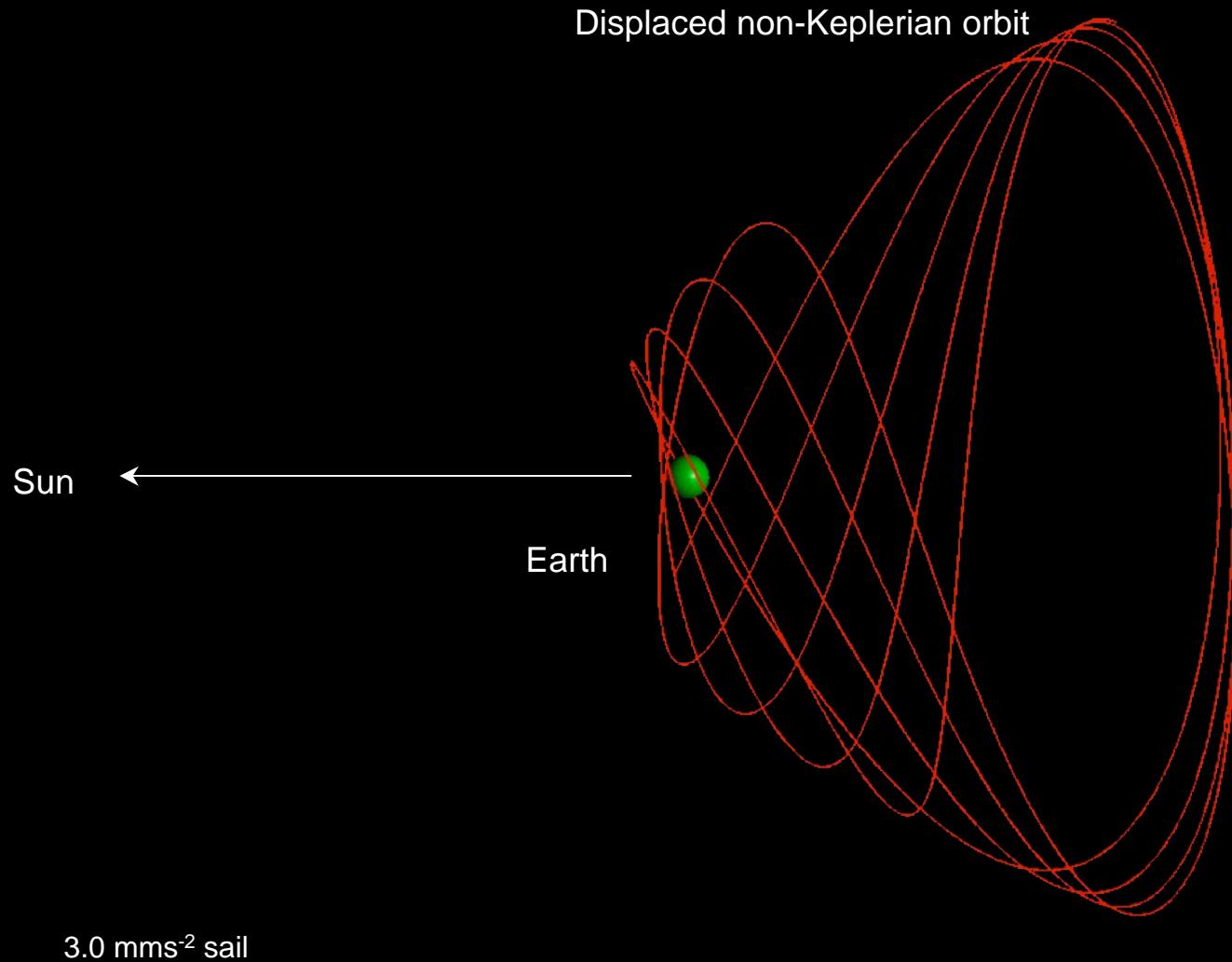
Sun-Centred Non-Keplerian Orbit



5.0 mms⁻² sail - 7 month trip



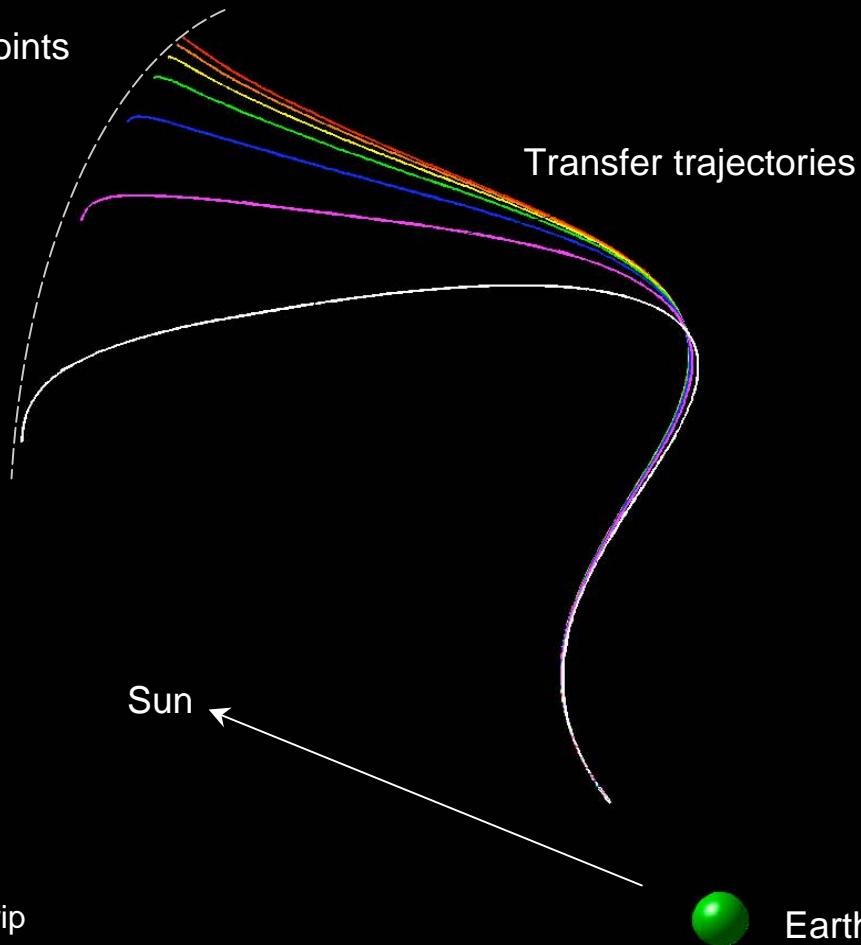
Earth-Centred Non-Keplerian Orbit





Artificial Lagrange Points

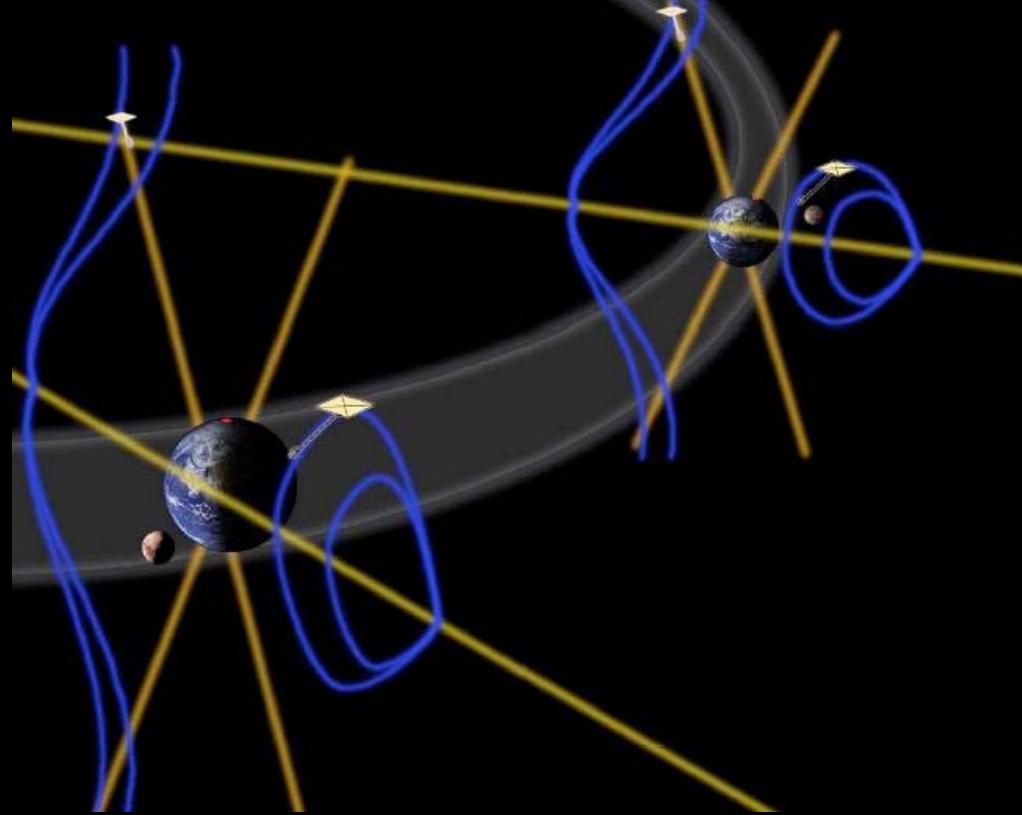
Family of artificial equilibrium points



0.32 mms⁻² sail - 120 day trip



Lagrange Point Pole-Sitters

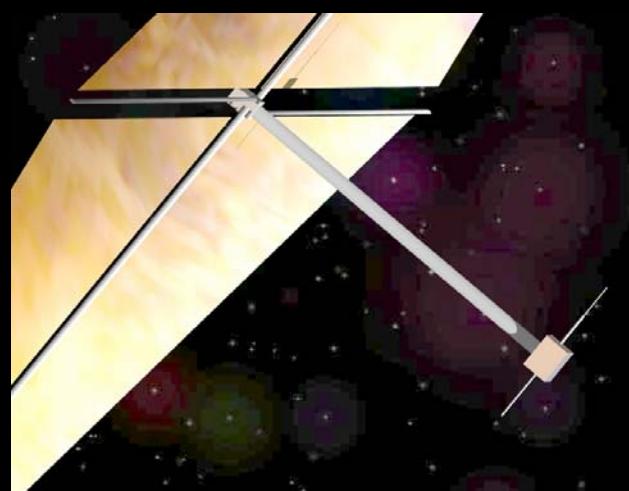
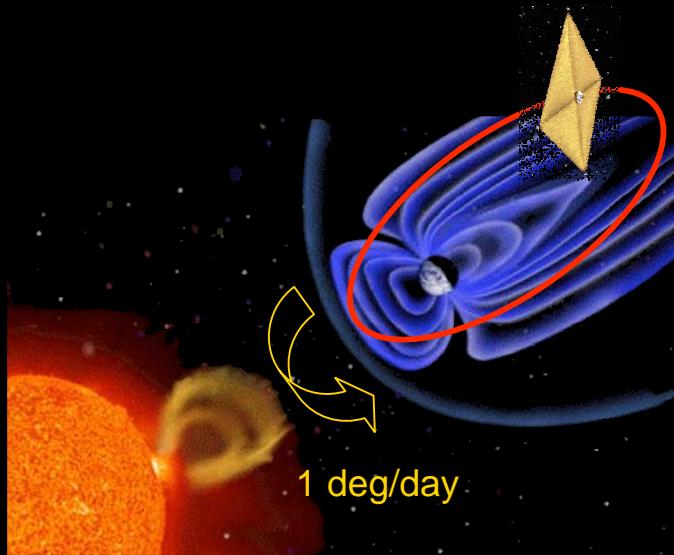


➤ Near Term Missions



GeoSail Mission

- Precess orbit apse line to stay permanently in Geomagnetic tail (in-situ science)
- Small 40 x 40 m solar sail with characteristic acceleration $\sim 0.1 \text{ mms}^{-2}$
- Demonstrate **new science capability** on technology demo mission



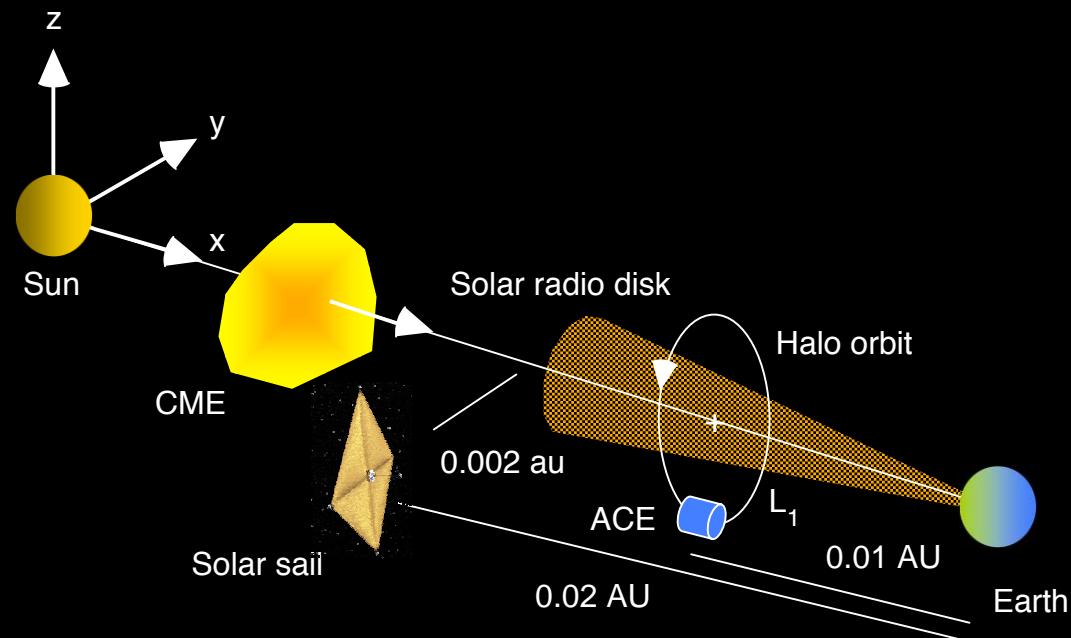


Mission Requirements

Parameter	Value	Unit	GEOSAIL
Sail size	40	m	Square sail
Assembly loading	38	g m ⁻²	
Char. acceleration	0.1	mm s ⁻²	for 11 x 23 Earth radii orbit
Film thickness	3.5	μm	
Max. sail temp.	-	K	
Bus mass	75	kg	field/particle instruments
Sail assembly mass	50	kg	
Launch mass	1015	kg	inc. bi-prop transfer stage
Launch vehicle	Vega		
Mission duration	2	yrs	base-line mission duration

GeoStorm Mission

- Can displace classical L_1 point sunwards using a modest solar sail
- Use magnetometer to detect polarity of solar wind field to detect solar storms
- Provide early warning (x 2) relative to spacecraft at classical L_1 point



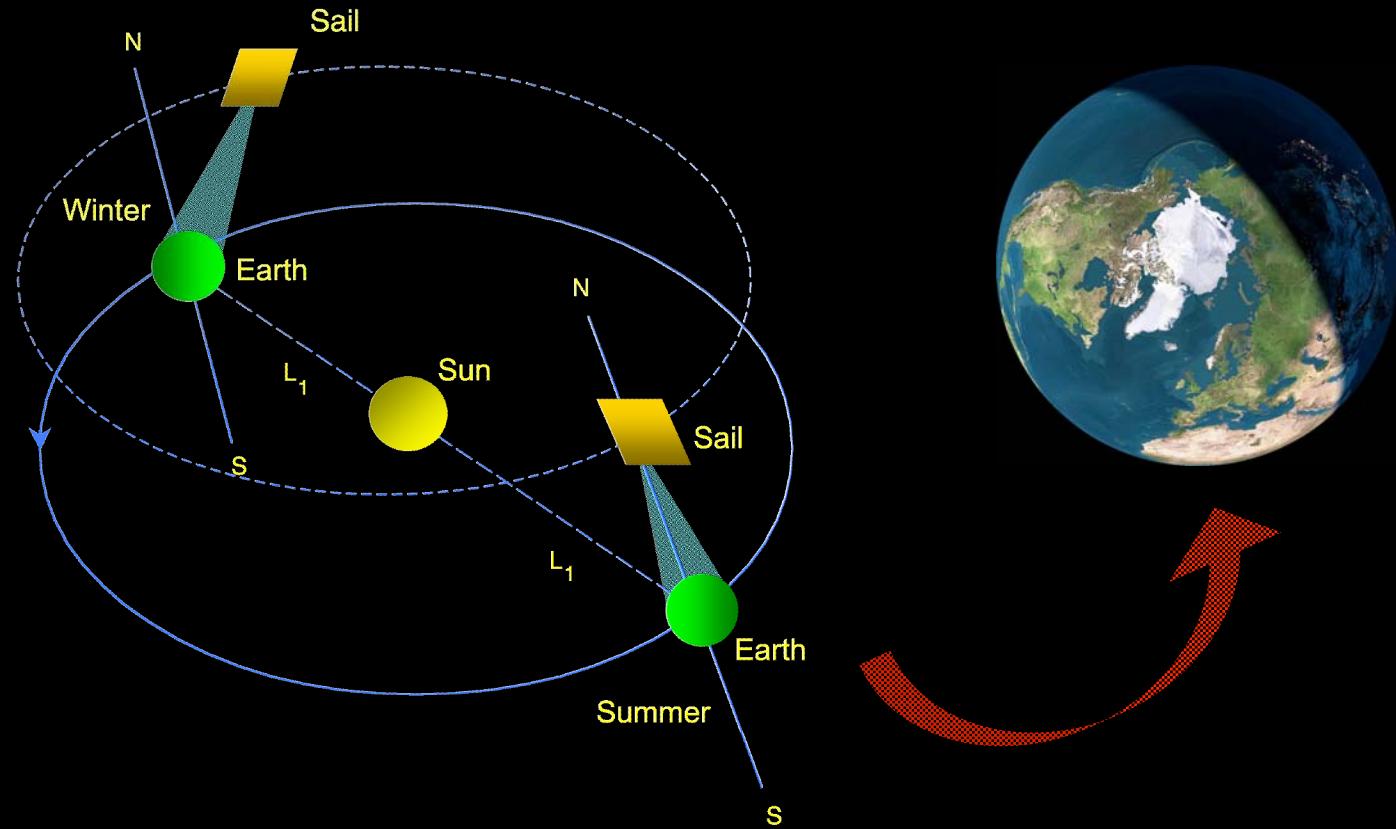


Mission Requirements

Parameter	Value	Unit	GEOSTORM
Sail size	79	m	Square sail
Assembly loading	14.5	g m ⁻²	
Char. acceleration	0.31	mm s ⁻²	for 0.98 AU solar orbit
Film thickness	3.0	μm	
Max. sail temp.	-	K	
Bus mass	79	kg	field/particle instruments
Sail assembly mass	90	kg	
Launch mass	257	kg	inc. kick stages
Launch vehicle	Eurokot/Star37FM		
Mission duration	2	yrs	+ 190 days to initial L ₁ station

Polar Observer Mission

- Can displaced classical L_1 point high above ecliptic plane
- Provide real-time hemispheric view of poles for climate studies
- Can also provide line-of-sight telecomms to high latitude users/stations



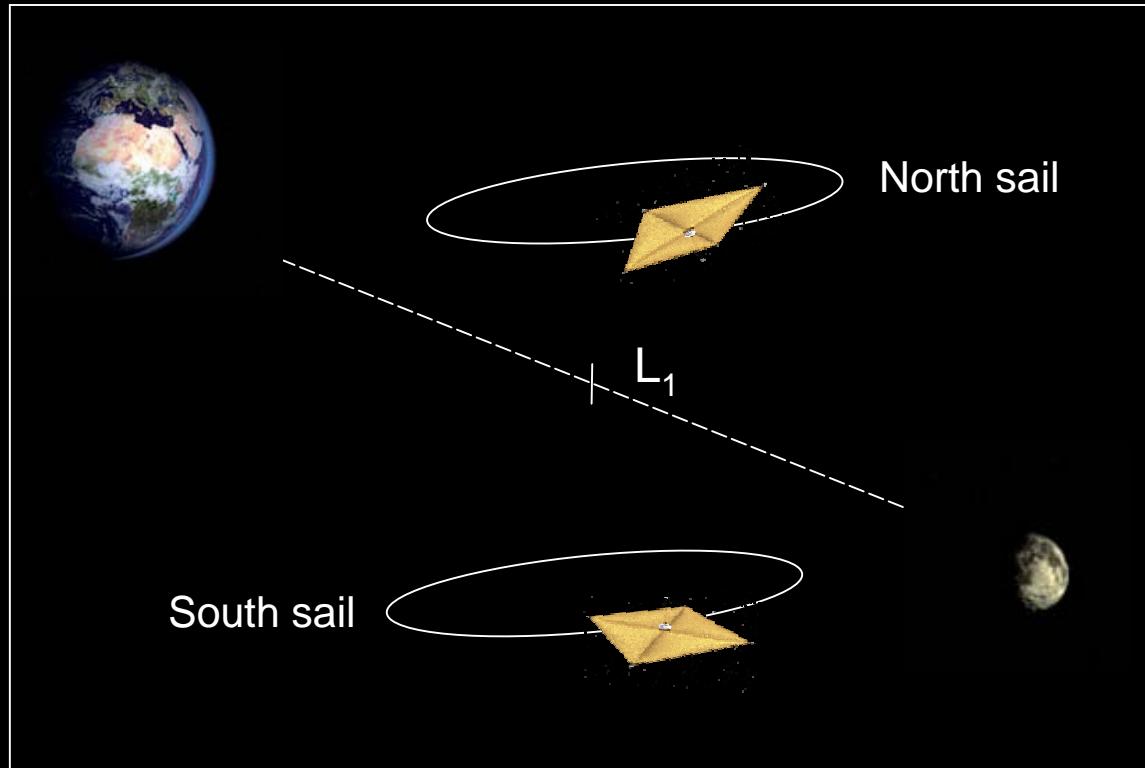


Mission Requirements

Parameter	Value	Unit	POLAR OBSERVER
Sail size	118	m	square sail
Assembly loading	9.0	g m ⁻²	
Char. acceleration	0.55	mm s ⁻²	for 3.8 million km altitude polar station
Film thickness	2.5	μm	
Max. sail temp.	-	K	
Bus mass	87	kg	ESA NAC instrument (98 km/pixel)
Sail assembly mass	125	kg	
Launch mass	212	kg	assuming sail transfer
Launch vehicle		Eurokot/Star37FM	
Transfer duration	2	yrs	+ 123 days to polar station

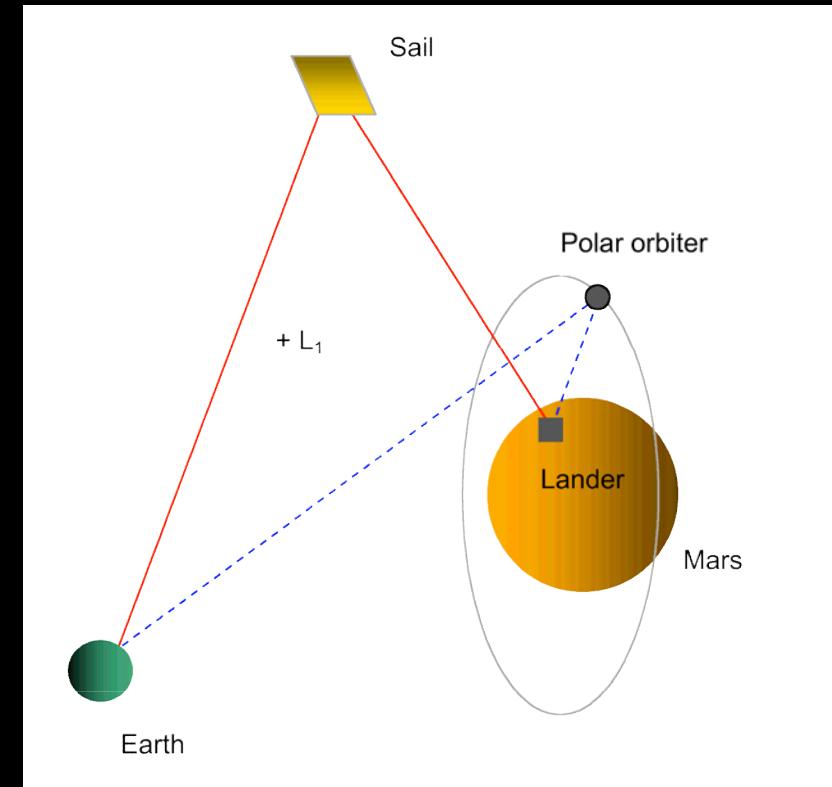
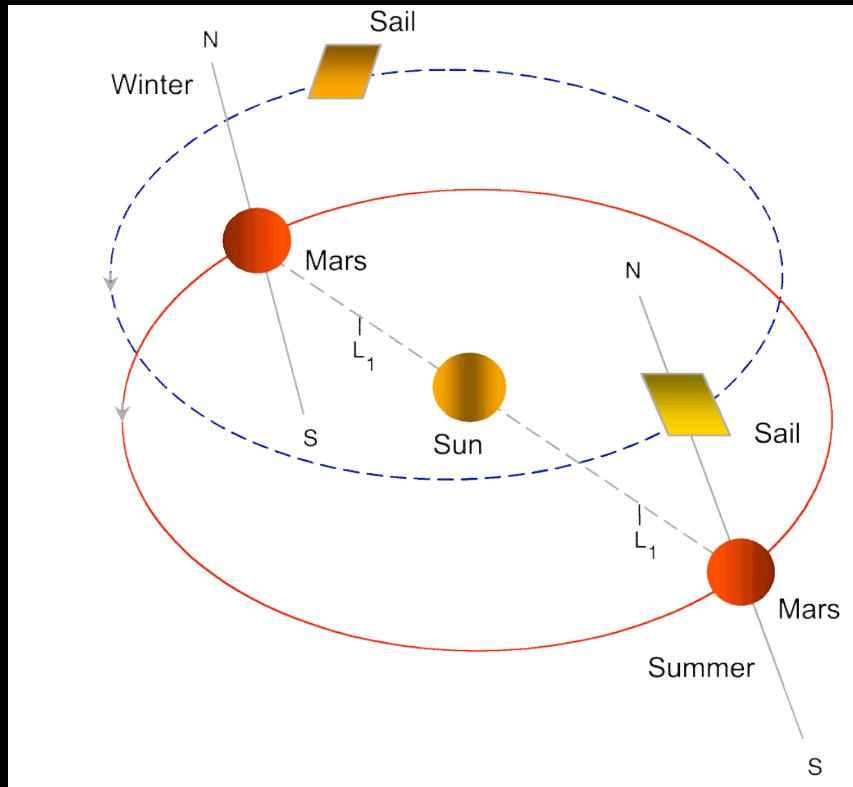
Lunar Telecommunications

- Sail can orbit above Earth-Moon L₁ point on narrow 28 day ellipse
- Provide continuous view of lunar poles for telecommunications relay
- Useful element of telecomms. architecture for future human lunar exploration



Mars Polar Relay

- Solar sail can hover at artificial Lagrange point over Mars polar regions ~500 Mars radii
- Continuous data return from polar lander (400 km orbiter has 8.7 min pass every 118 mins)
- Applications for missions with long-stay surface rover/ human exploration

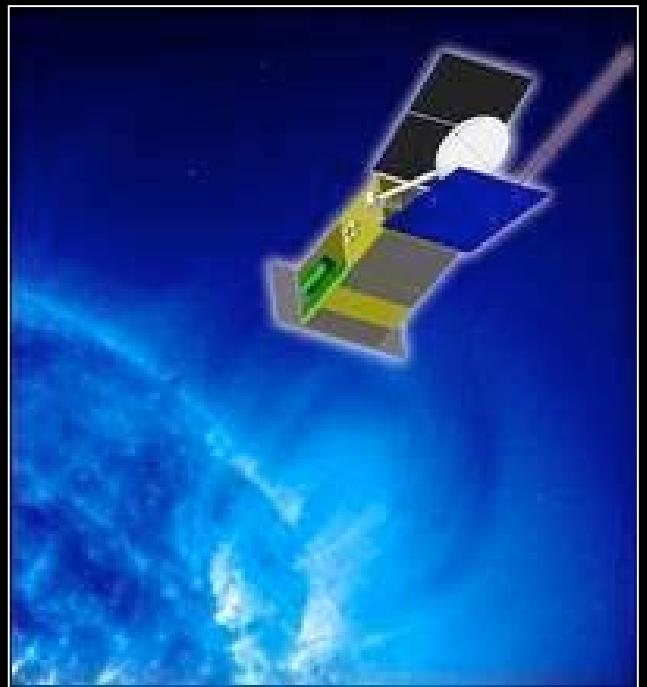


➤ Mid-Term Missions



Solar Polar Orbiter Mission

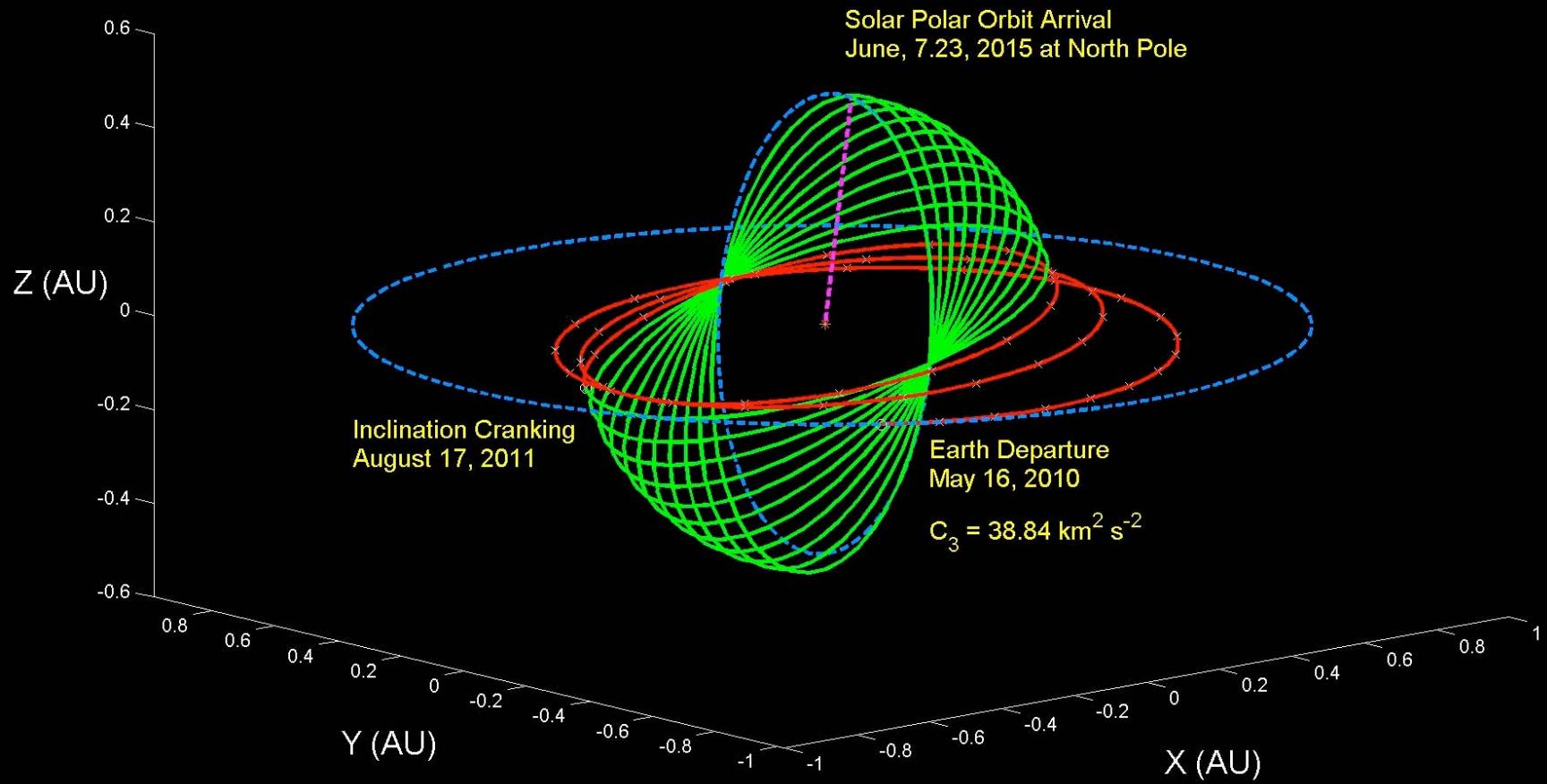
- Ulysses provided field and particle data at high solar latitudes (but long re-visit)
- ESA F-class SOLO mission will reach only 30-38° ecliptic inclination using SEP
- Solar sailing appears the only realistic propulsion option for a true solar polar mission*



* See poster session - Technology Reference Studies Using Solar Sails, A. Lyngvi et al

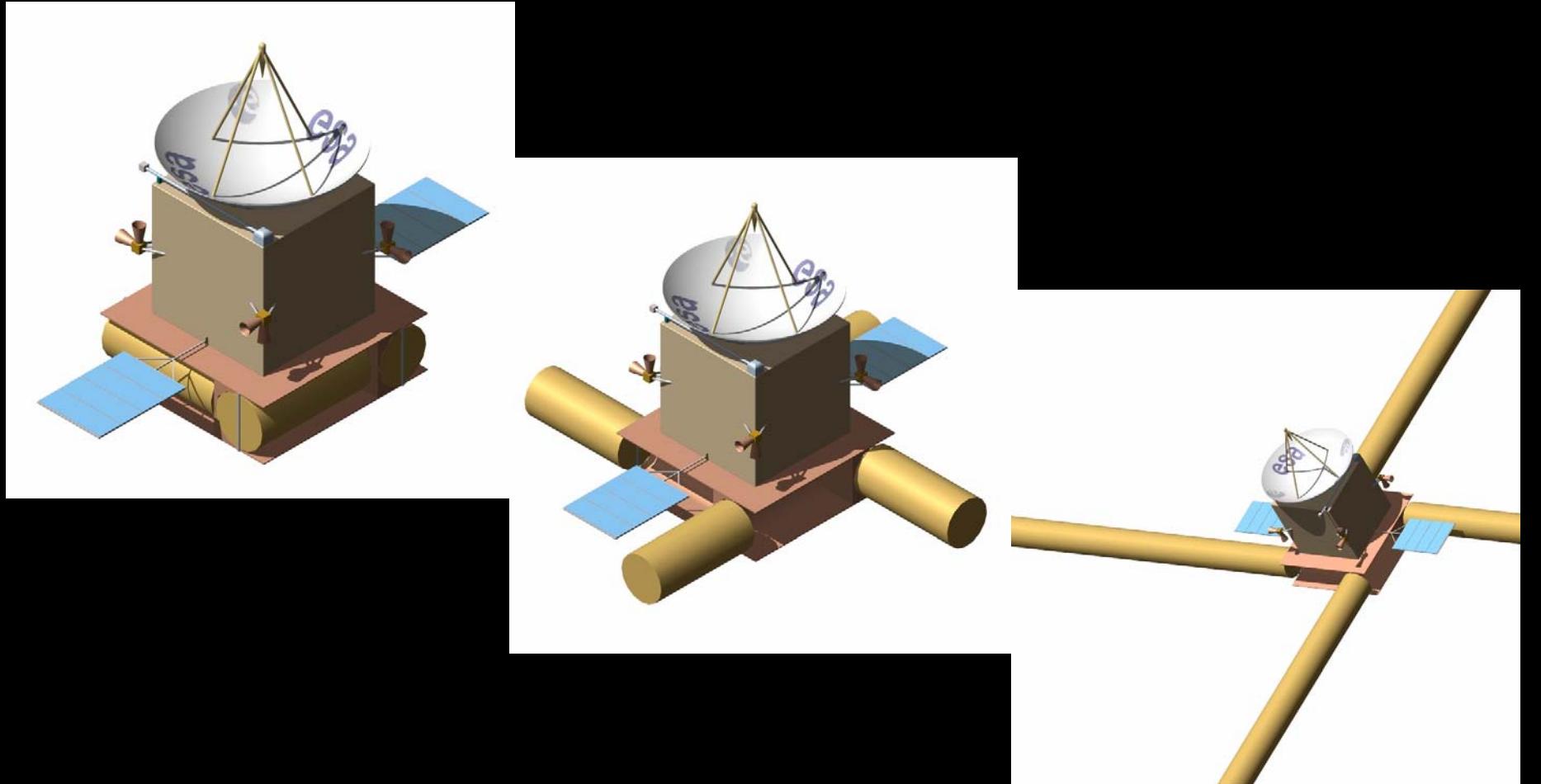


Transfer Trajectory



0.4 mms⁻² sail with cranking at 0.48 AU

Sail Deployment





Mission Requirements

Parameter	Value	Unit	SOLAR POLAR ORBITER
Sail size	153	m	square sail
Assembly loading	8.0	g m^{-2}	
Char. acceleration	0.42	mm s^{-2}	for 5 yr transfer + 0.3 AU cranking orbit
Film thickness	2	μm	
Max. sail temp.	390	K	at 0.48 AU cranking orbit
Bus mass	248	kg	field/particle + coronograph/EUV imager
Sail assembly mass	196	kg	
Launch mass	444	kg	with margin
Launch vehicle	Soyuz ST-Fregat		to max available C_3
Mission duration	7	yrs	5 yrs cruise + 2 yrs science

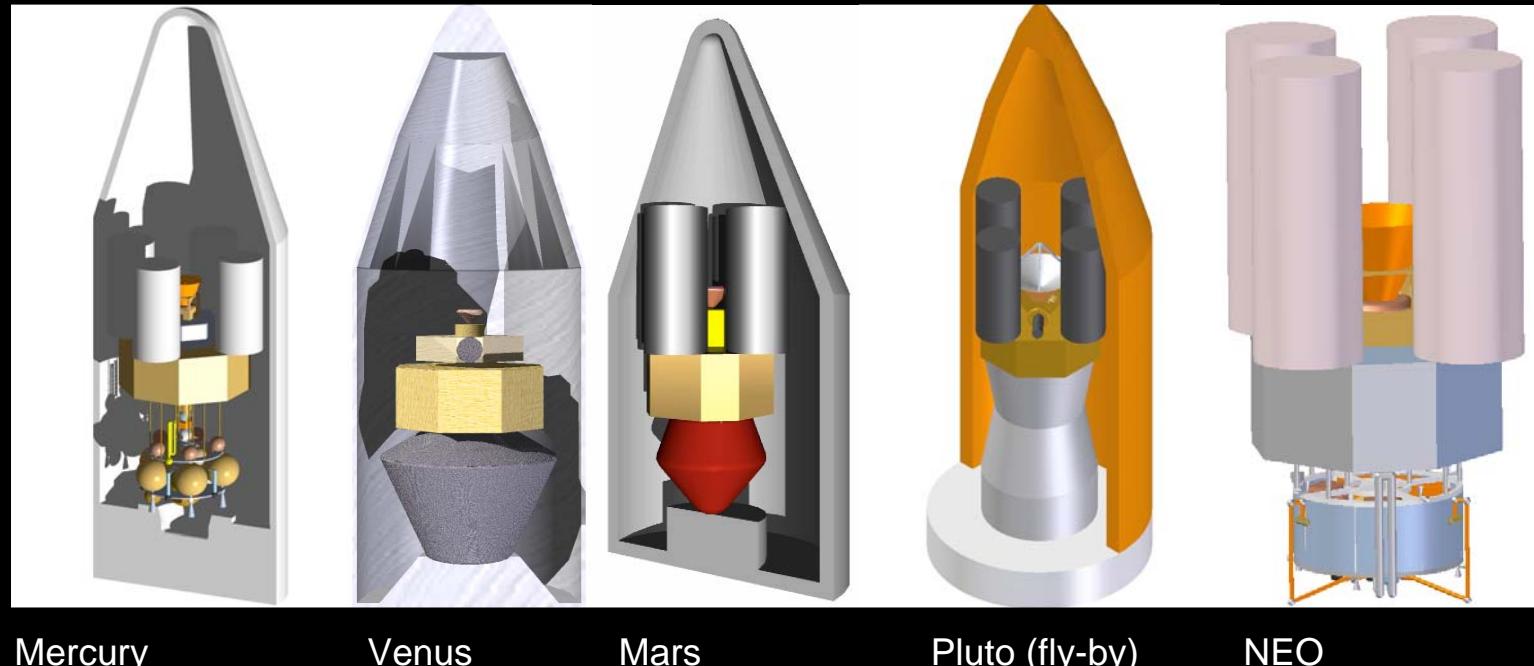


Planetary Fly-by and Sample Return

Reduce future high-energy science mission costs/ flight time using solar sail propulsion

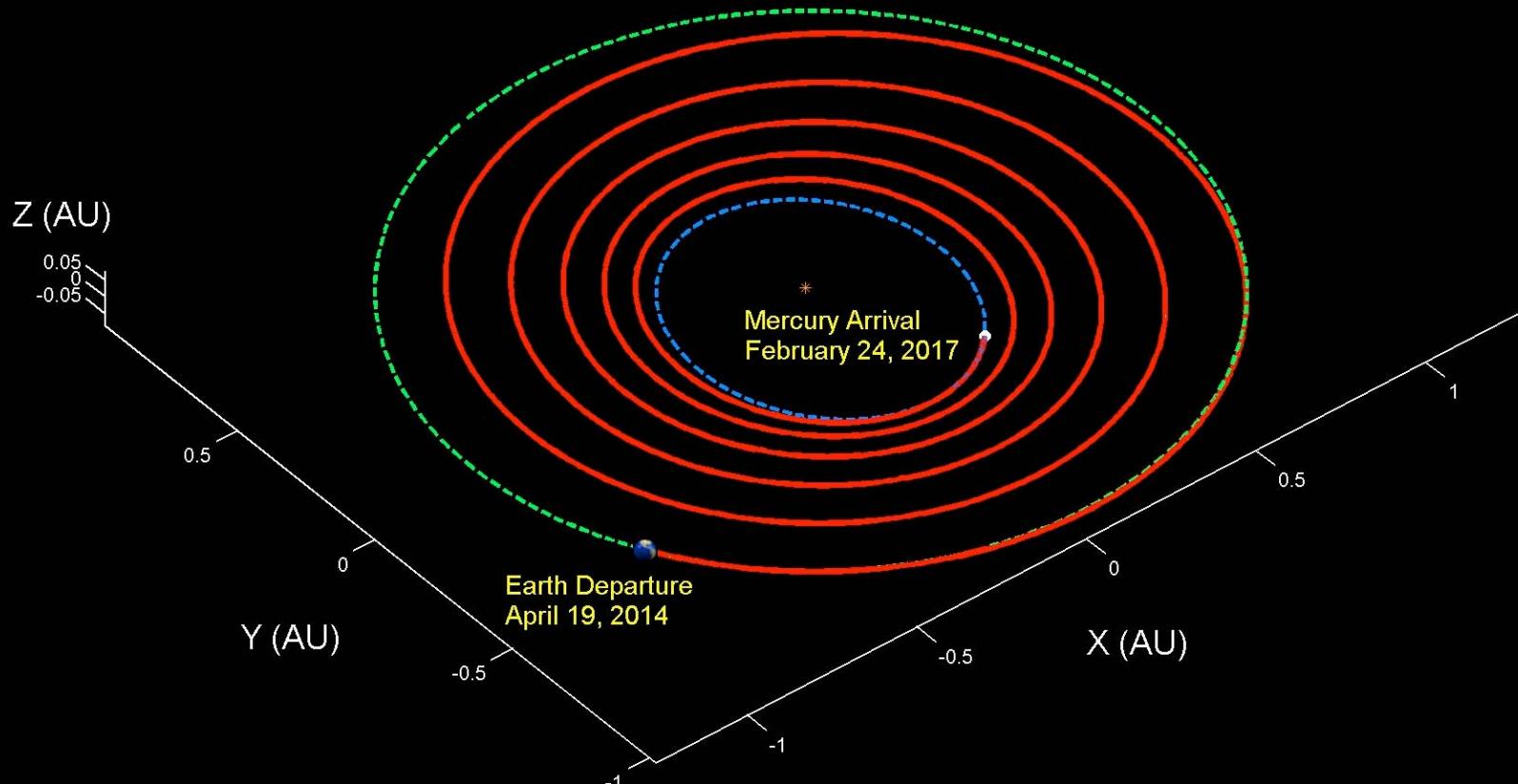
Extensive study for ESA of concepts for sample return missions (Mars, Venus, Mercury, NEO)

Systems engineering analysis with coupled trajectory optimisation and spacecraft design/sizing



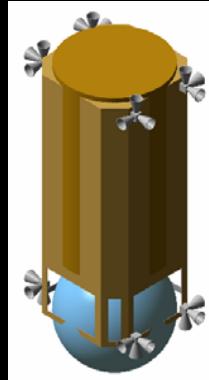


Earth-Mercury Phase

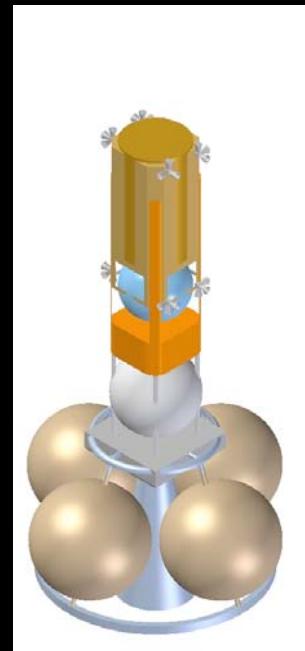


0.25 mms⁻² inbound spiral

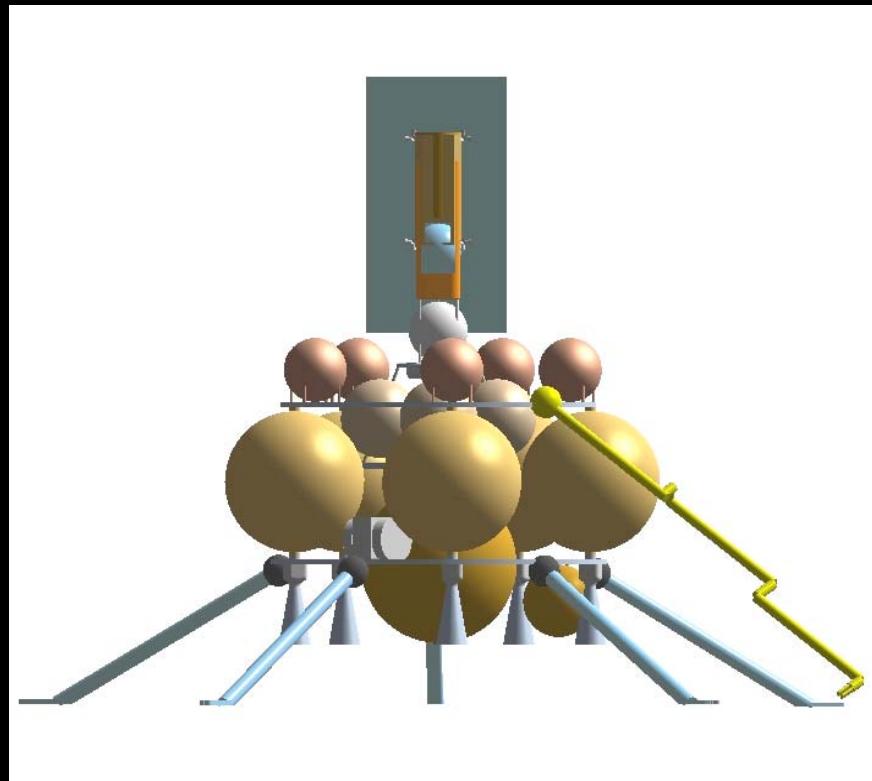
Mercury Lander Configuration



Rendezvous vehicle
(15 kg – 2 kg canister)



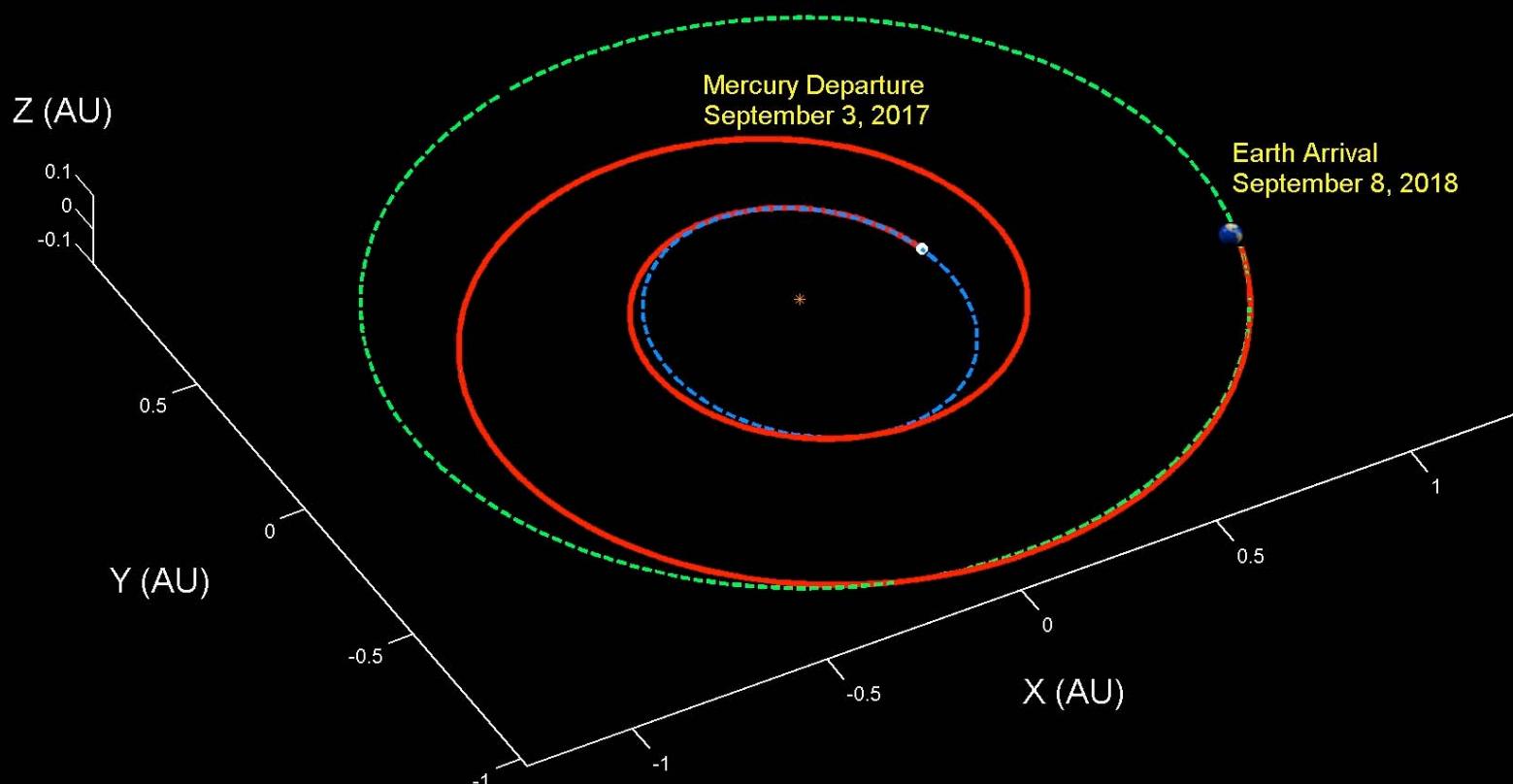
Ascent stage
(160 kg – 1 x 3.5 kN)



Ascent/descent stages
(Lander 1280 kg – 5 x 5 kN)

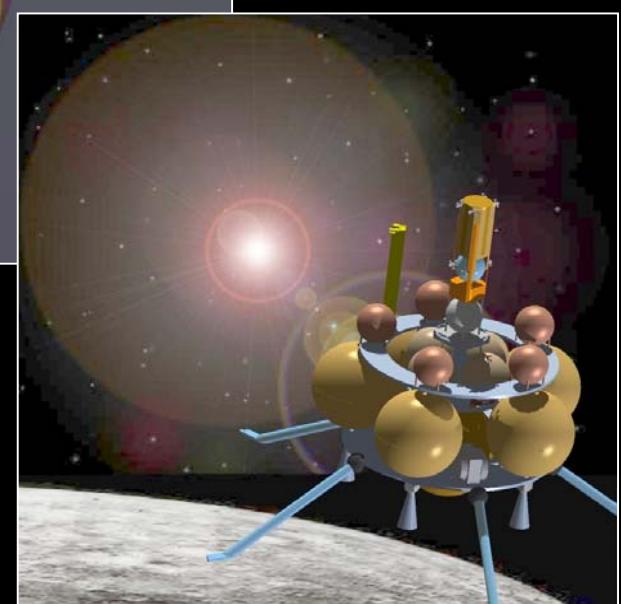
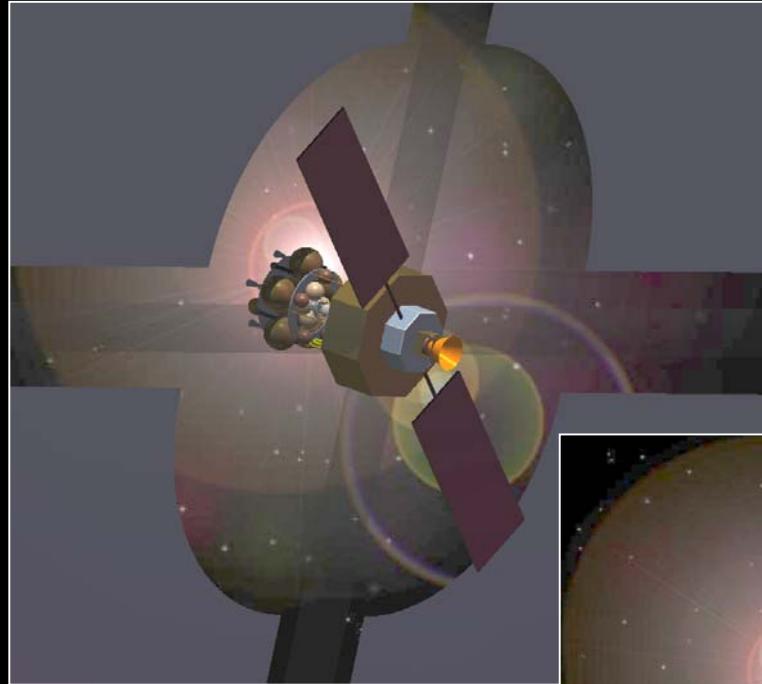
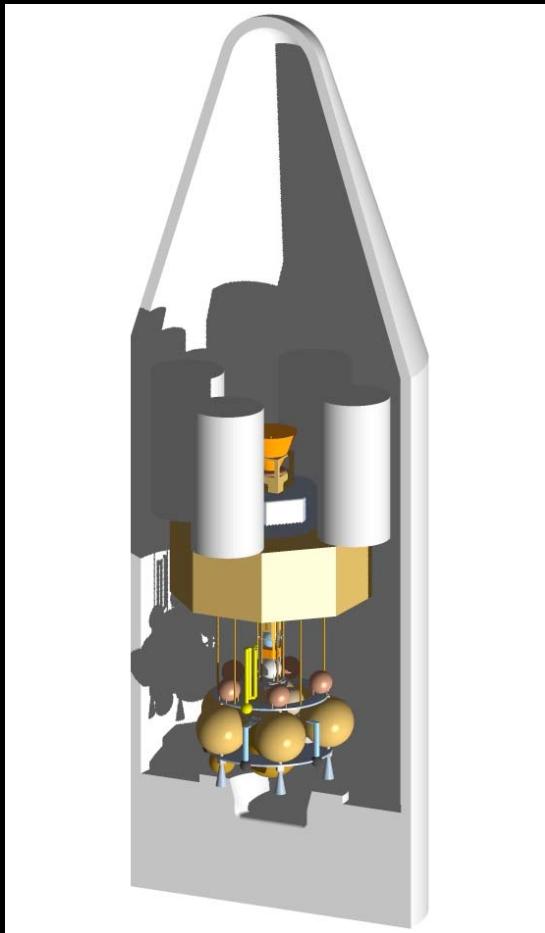


Mercury-Earth Phase



0.78 mms⁻² return spiral

Sail Deployment





Mission Requirements

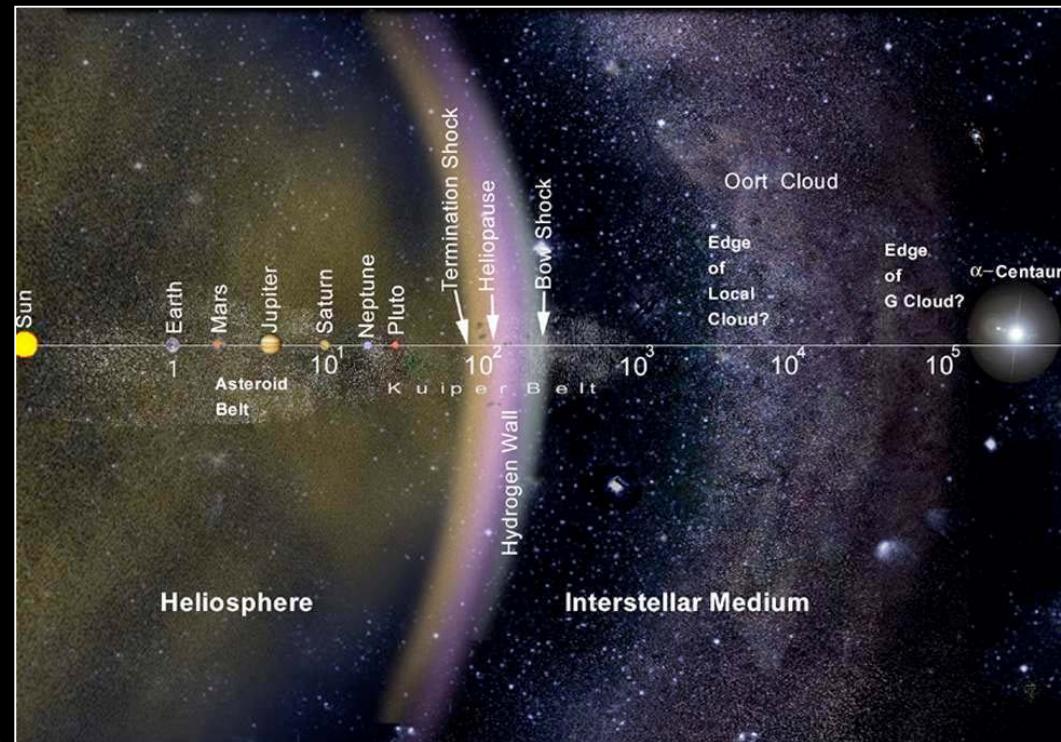
Parameter	Value	Unit	MERCURY SAMPLE RETURN
Sail size	276	m	Square sail
Assembly loading	5.9	g m ⁻²	
Char. acceleration	0.25	mm s ⁻²	return acc. 0.78 mm s ⁻²
Film thickness	2	μm	
Max. sail temp.	495	K	
Bus mass	1905	kg	orbiter + lander/ascent vehicle
Sail assembly mass	448	kg	
Launch mass	2353	kg	with margin
Launch vehicle	Zenit 3-SL		to C ₃ =0
Mission duration	4.4	yrs	without Venus fly-by

➤ Far-Term Missions



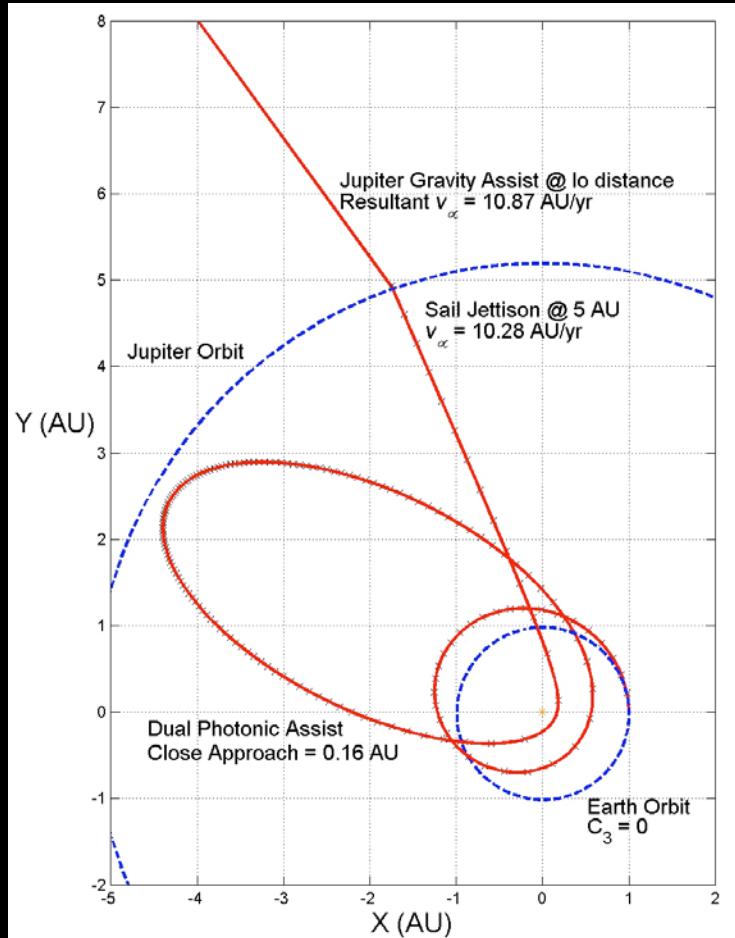
Interstellar Heliopause Mission

- Expect heliopause at 120-170 AU formed by interaction of solar wind and ISM*
- Chemical propulsion would require large burn at 4 solar radii (C-C heat shield)
- SEP requires (lengthy) multiple solar loops to avoid gravity losses
- NEP (and SEP) pose problems for science payload (sail jettison at 5 AU)

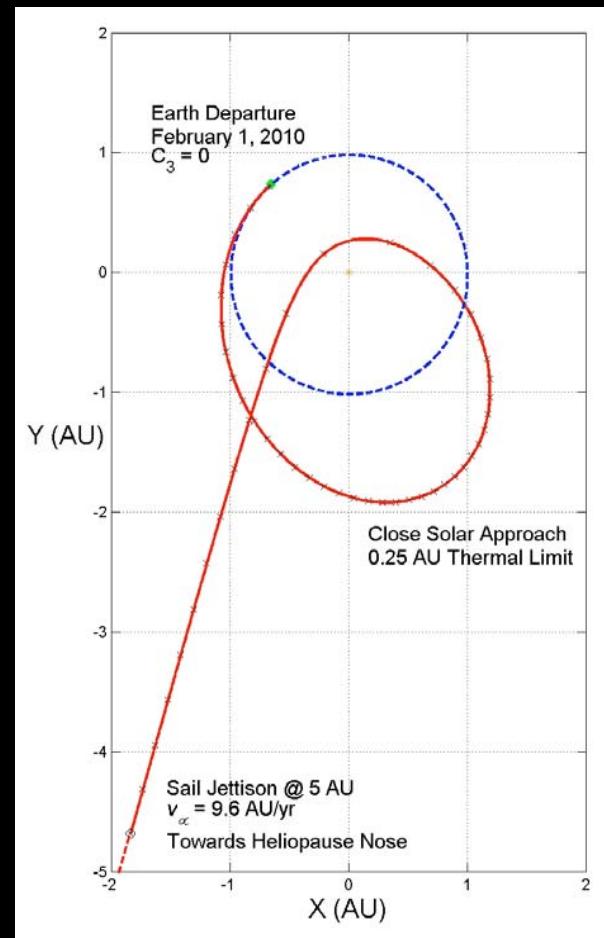


* See poster session - Technology Reference Studies Using Solar Sails, A. Lyngvi et al

Escape Trajectories

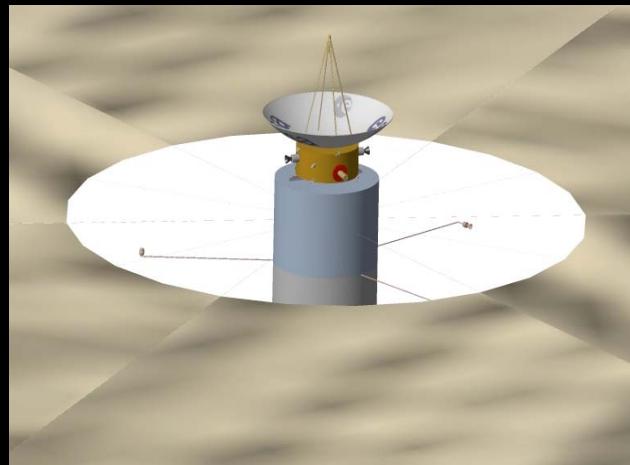
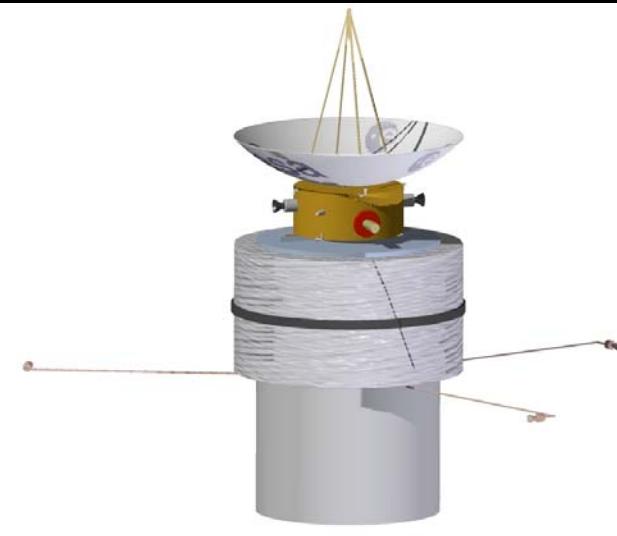
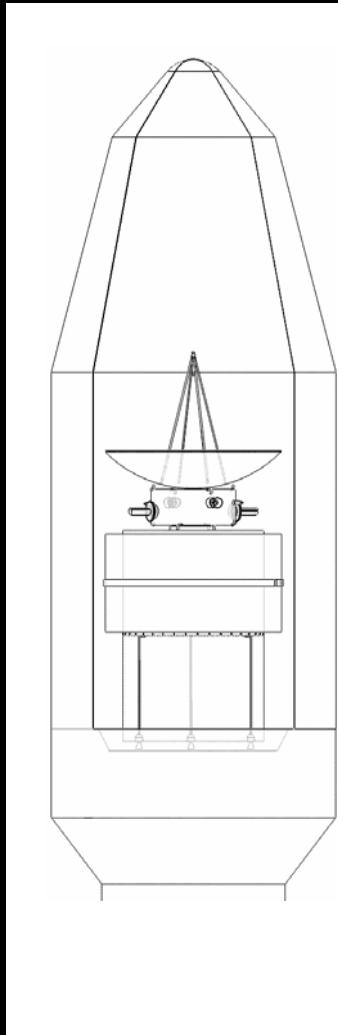


25 year 0.85 mm s^{-2} trajectory (0.16 AU perihelion)



25 year 1.5 mm s^{-2} trajectory (0.25 AU perihelion)

Sail Deployment



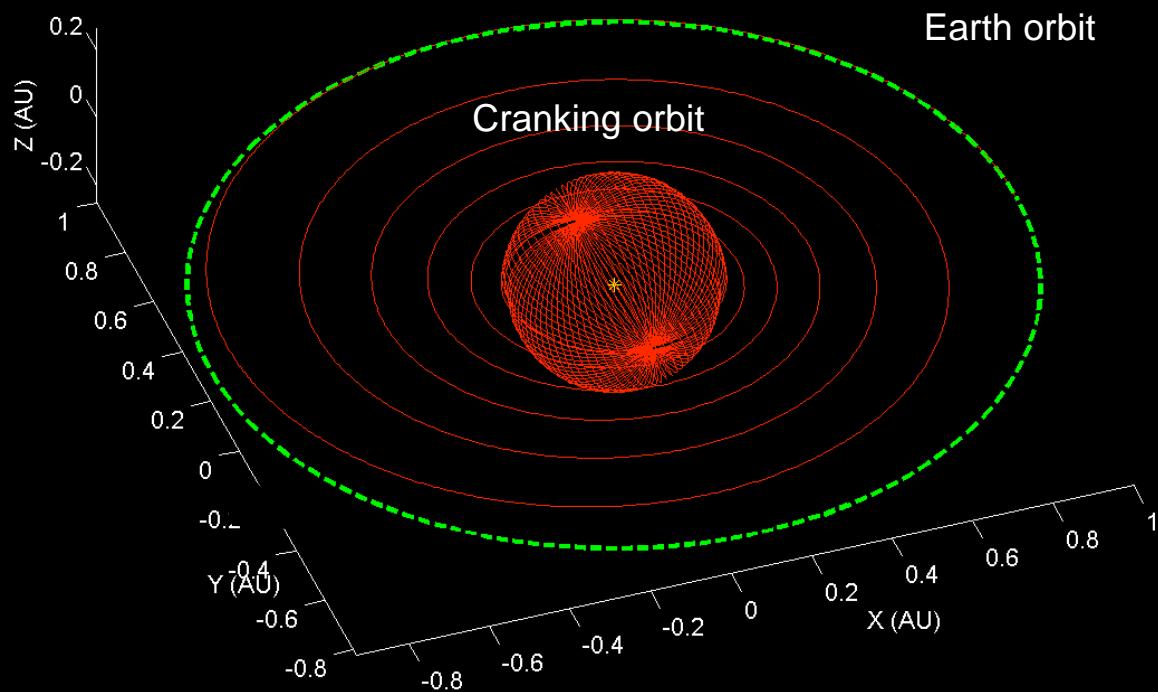


Mission Requirements

Parameter	Value	Unit	HELIOPAUSE PROBE
Sail size	137	m	disk sail
Assembly loading	1.8	g m ⁻²	
Char. acceleration	1.5	mm s ⁻²	for single close solar pass
Film thickness	1	μm	
Max. sail temp.	501	K	at close solar pass
Bus mass	198	kg	field/particle + cosmic ray/dust detectors
Sail assembly mass	107	kg	
Launch mass	606	kg	inc. sail spin-up stage
Launch vehicle	Soyuz ST-Fregat		to C ₃ =0
Mission duration	25	yrs	to 200 AU

NEO Deflection

- Non-nuclear scheme to deflect potentially hazardous NEOs by kinetic energy impacts
- Use **retrograde orbit** to deliver kinetic energy impactor to NEO at 60 km s^{-1}
- Can alter orbits of 1-2 km sized NEOs with 300x300 m sail and 2500 kg impactor



Inclination cranking to 180° retrograde orbit



Stowed sail with 2500 kg impactor

➤ Future Prospects

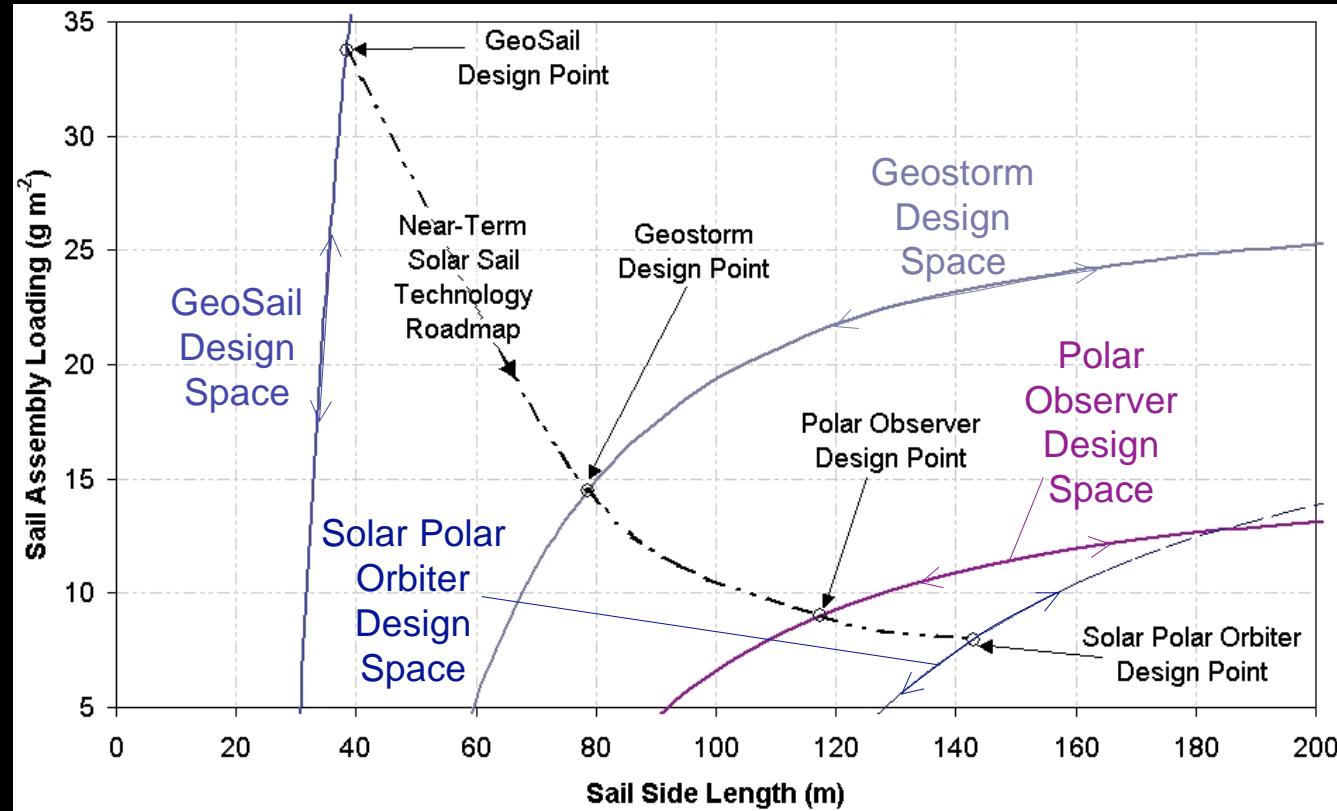


Mission Requirements Matrix

Mission	Ac (mm s ⁻²)	Size (m)	Assembly load (g m ⁻²)	Mission PI
GeoSail	0.10	40	33.7	Space physics
Geostorm	0.31	79	14.5	Space weather
Polar Observer	0.55	118	9.0	EO/telecomms.
Solar Polar Orbiter	0.41	153	8.0	Solar physics
Mercury Sample Return	0.35	276	5.9	Planetary
Heliopause Probe	1.50	137 (disk)	1.8	Space physics

Near Term Roadmap

- Several compelling mission applications early in roadmap (even with demo class sail)
- Component technologies for first mission available, but no systems integration yet
- Initial missions need to over-reach requirements to open path to next roadmap mission





Outlook for Solar Sailing

- Solar sailing can enable exciting new missions for science, operations and human exploration
- Provide unique orbits/vantages points for space science, Earth observation, telecomms.
- Technology demonstration can validate solar sailing, but must lead somewhere in the long term
- Need to identify compelling near-term mission concepts to balance long term vision
- Since mid-1990s solar sailing has steadily progressed - several near misses to reach flight
- Upcoming opportunities to progress solar sailing in US, Europe and Japan . . .



what are we waiting for . . . ?

